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PLANETARY FRICTION TRANSMISSIONS

W. E. Elford, C.Eng., M.I.Mech.E., R.N.S.S.
Admiralty Research Laboratory

William E. Elford entered Chatham Dockyard as apprentice in 1931, entering the Drawing Office there in 1937. In 1939 he transferred to the DO at ARL Teddington, working on remote power control and control systems for guided weapons. In 1947 he was made EO through open competition in the scientific service reconstruction. When the guided weapon work ceased at ARL/AGE in 1951 he transferred to the pressure mine countermeasure group and subsequently to the active submarine detection group. He was promoted to SEO in 1956, becoming a member of the Engineering research group working on the problem of waterside attack in diesel engines. Promoted to PSO in 1963, he is now a member of the new machinery noise research group recently brought into being at ARL.

Introduction

Friction transmissions, *i.e.* units which use the friction forces generated by normal loading between two or more moving parts to transmit power, are not new. Indeed, over the last 100 years or so many differing forms have appeared in technical and commercial literature, but mostly these have been of the variable ratio type and limited to relatively low powers. In most cases, these units rely on virtual " point " contact between rotating surfaces, hence the loading which can be applied is strictly limited if contact stresses (Hertzian stresses) are not to be excessive. It is possible however to design fixed ratio transmissions in a planetary configuration, where the power is transmitted by friction forces generated between two parallel rolling surfaces, *i.e.* cylinders, (in which case the contact is of a " line " nature), and which can transmit far greater torques.

The simplest form of planetary friction transmission is the epicyclic type, shown diagramatically in Fig. 1, where a number of plain cylindrical rollers are interposed between a central " sun " roller and outer ring. If the outer ring is loaded onto the " planet " rollers, and these loads are transmitted through the planets to the " sun ", the friction forces generated at the roller contacts enable power to be transmitted when one or other member is rotated. Generally this form of transmission will have power input to the sun with the output taken from the planet cage, as this gives the higher reduction ratio. The units may also be used as a " step-up " transmission when input is to the planet cage.

Planetary friction transmissions are not however limited to a single row of planets and may be arranged with any number of convenient rows. These assemblies, generally known as " Multi-Roller " transmissions, may be built with very high reduction ratios—up to about 600: 1 for a four row drive—and may be very compact compared with conventional gear reducers. They are also capable of transmitting much higher speeds than those which could successfully be used with gear trains.

By far the most important property as far as MOD is concerned is that they have very low noise and vibration characteristics—much lower than any other known transmissions. It is this feature which makes them a very attractive proposition for such things as torpedo power drives, although this is by no means the only possible application. They also provide a useful tool in the research field for the study of high rotational speed phenomena.

In 1966, a paper presented by Nasvytis[1] to the SAE outlined some work carried out by TRW Inc., for the US Defence Dept., on multi-roller planetary transmissions, and which gave results of tests on several units. Unfortunately the experimental units did not live up to expectations, difficulty being experienced in obtaining satisfactory pre-loading of the rollers and stability of the planet assembly. These adverse factors could be directly attributed to the method used for obtaining the pre-load forces.

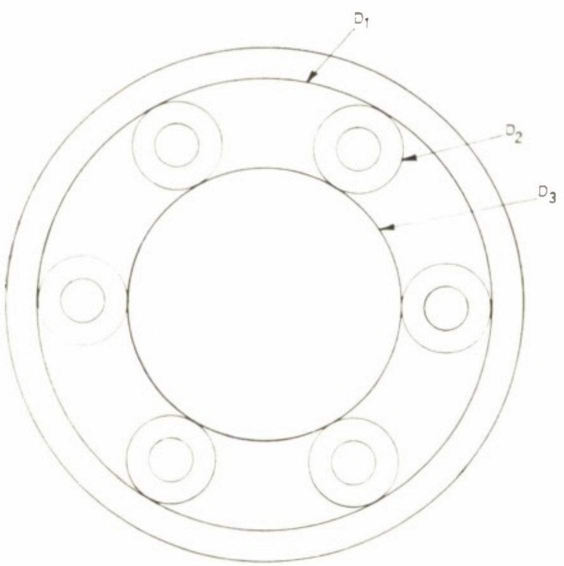

FIG. 1. Simple Epicyclic Transmission.

Despite the shortcomings in design, TRW managed to run a three row transmission as a 120: 1 step-up unit for 43 consecutive hours in the unlubricated state at 360,000 rpm output—albeit at only 2 - 3 HP.

General Motors (USA) have also marketed a planetary friction transmission in which the cylindrical rollers were replaced with conical ones, the cone angles being chosen to prevent unwanted " slip " at the contact lines. Preloading of these units is achieved by end loading the conical planet spindles, but since the planets are mounted on these spindles *via* ball and roller bearings, (which have to take fairly heavy end loads), quiet running would be impaired. This form was also recently put forward by a British firm in a design study for an electric drive torpedo.

Pre-loading methods

Two methods of pre-loading the planet assembly were used by Nasvytis, (a) thermal shrinkage of the outer ring over the planets, and (b) using the " toggle " action available on the three row planet drives of the N-2N-2N type (see later section describing types).

Thermal shrink fitting the outer ring has disadvantages in as much as the ring has to be " sized " to a high degree of accuracy, the pre-load is sensitive to changes of temperature during running, and it is difficult to dissemble the unit for inspection or repair. Disadvantages of the " toggle " action method are given later when the relevant types are discussed.

At ARL, much interest was shown in the Nasvytis paper, and the difficulties encountered were fully appreciated. Consideration was therefore given to finding an alternative method of pre-loading which did not suffer the disadvantages of the previous methods. The solution was eventually found in using external hydraulic pressurisation[2] of the ring, to contract the ring on to the planet assembly. It was felt that this method would have several advantages over the other systems, *viz:*—

(i) Changes in pre-load due to wear of moving parts or by temperature changes could be accommodated by increasing/decreasing the hydraulic pressure.

(ii) Initial sizing of the ring would not be as critical.

(iii) The load could easily be removed when the unit was standing idle—hence the chances of "Brinelling" the rollers would be reduced—and also, the unit could be dismantled easily.

(iv) By providing some damping at the hydraulic pressure seals, natural vibration amplitudes would be reduced.

(v) Stresses imposed by the hydraulic pressure tend to nullify those imposed by the outward loads of the planets.

To prove the hydraulic pressurisation method, a simple epicyclic transmission was designed, manufactured and tested, the main objects being to see how close the theoretical design could be realised in practice and to gain knowledge on variations of parameters used in the design. A description and results of tests of this unit are given later—(see Experimental Designs).

Possible Planet Arrangements

Generally, the arrangements of planets in fixed ratio transmissions may be divided into the following broad categories:—

(i) Simple epicyclic transmission having one row of plain planets.

(ii) Compound epicyclic transmissions having one row of "stepped" planets.

(iii) Transmissions with two rows of planets —either "stepped" or plain.

(iv) Transmissions with three rows of planets—either "stepped" or plain.

(v) Transmissions with four or more rows of planets—either "stepped" or plain.

Transmissions may have any number of planets per row as found convenient to the transmission ratio required, but not necessarily the same number of planets in each row within a given unit.

Overall characteristics of the various types may be given as follows:—

(i) Simple epicyclic type (Fig. 1)

These may be used for transmission ratios —sun to planet carrier—between 2 and 10:1 reduction. The actual number of planets used depends on the ratio and the practical aspect of using the spaces between planets to accommodate the planet cage and bearings. Thus in the diagram shown (Fig. 1), although it is geometrically possible to insert 12 planets in the annulus between the sun and ring, only six (or possibly eight) would be used. The ratio obtainable is

$$\left[\frac{D_1}{D_3}\right] + 1 \text{ — sun to planet cage,}$$

the output being in the same direction as the input to the sun.

(ii) Compound epicyclic type (Figs. 2(a) and 2(b))

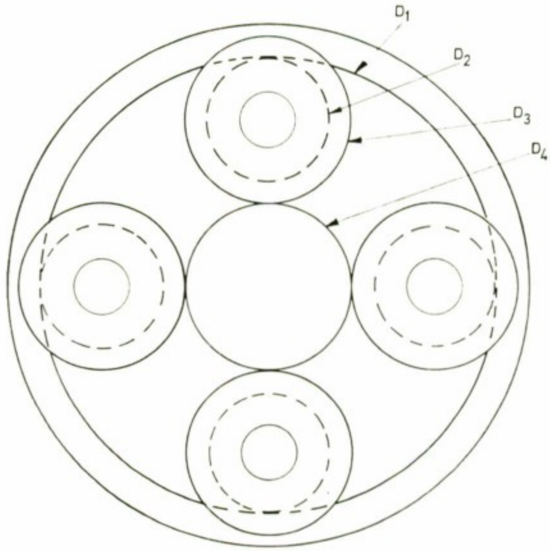

FIG. 2(a). Compound Epicyclic Transmission(1).

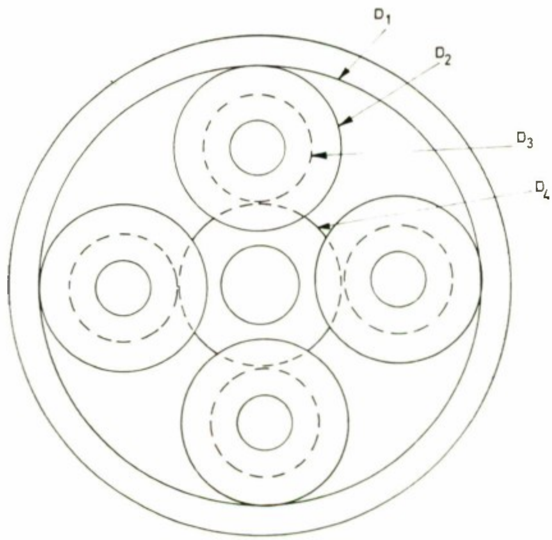

FIG. 2(b). Compound Epicyclic Transmission(2).

This type has one row of stepped planets and may have two configurations as shown. They may be used to somewhat extend the range of reduction ratios obtainable with the simple epicyclic type.

The ratios obtainable are:—

$$\left[\frac{D_1}{D_2} \times \frac{D_3}{D_4}\right] + 1 \text{ — sun to planet cage,}$$

the output being in the same direction as the input to the sun.

(iii) **Two row planet type (Fig. 3)**

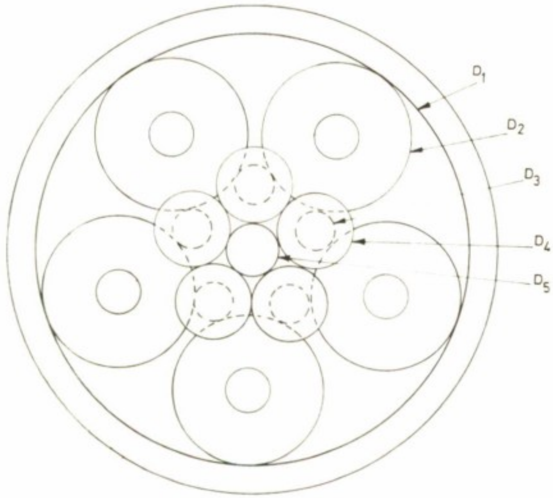

FIG. 3. Two Row Transmission.

This type may be used for transmission ratios up to about 24:1. Fig. 3 shows an arrangement having five planets per row, the outer row being plain. The ratio is

$$\left[\frac{D_1}{D_2} \times \frac{D_2}{D_3} \times \frac{D_4}{D_5}\right] - 1 \text{ — sun to planet cage,}$$

the output being in the reverse direction to that of the sun.

The planet arrangement is " self centreing " and thus only the outer row of planets need have bearings to transmit torque from the planet cage.

One interesting variant of this type is one which has a sun roller one half of the diameter of the outer ring, with two rows of plain rollers interposed between them. The ratio of such a unit is 1:1, with the planet cage output opposite to the sun. Thus it is possible to directly reverse a given drive, or to split the output from a previous transmission into a complementary contra-rotating pair.

(iv) **Three row transmissions**

These may be arranged to give reduction ratios up to about 120:1. There are three possible planet arrangements as follows:—

(a) N—N—N— shown in Fig. 4
(b) N—2N—2N— shown in Fig. 5
(c) N—N—2N— shown in Fig. 6

where N=No of planets in the first row (next to sun)

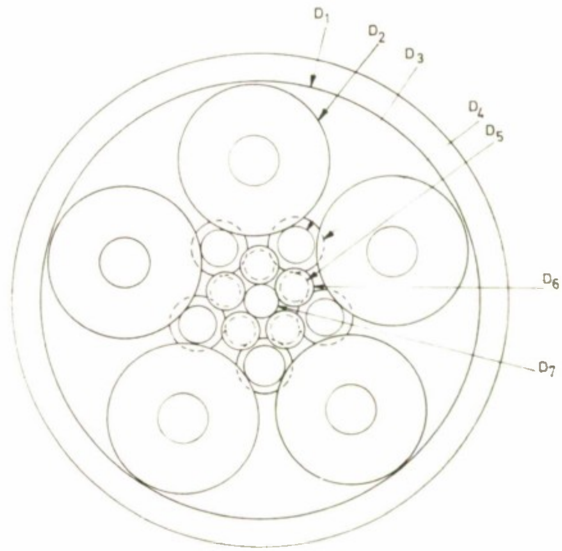

FIG. 4. Three Row Transmission N-N-N Arrangement.

The N—N—N type is a stable self centring arrangement, only the outer row of planets needing bearings to transmit output torque.

The N—2N—2N type is the one used by Nasvytis to obtain roller pre-loading.

It is easy to appreciate that if alternate rollers in the outer row are moved circumferentially with respect to the remainder, a " toggle " action is imposed on the first row planets which will vary the loading between them and the sun from zero to a maximum. Unfortunately when power is transmitted, the loading between the outer row planets and the ring is not the same for all planets, the ring tending to deflect in the N mode rather than the 2N. This leads to instability of the planet cluster.

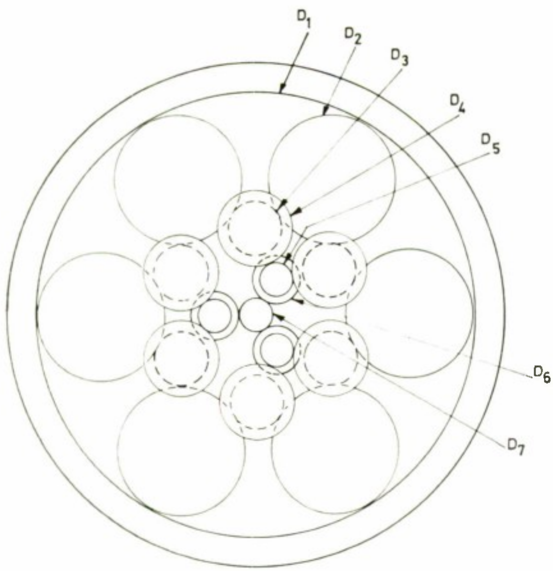

FIG. 5. Three Row Transmission N-2N-2N Arrangement.

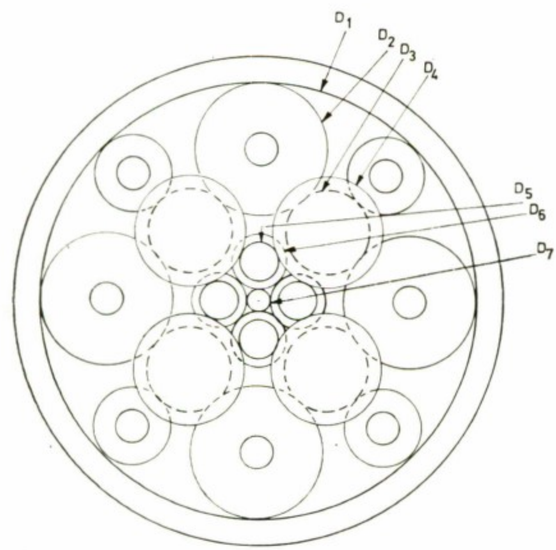

FIG. 6. Three Row Transmission N-N-2N Arrangement.

If this method of pre-loading is adopted, it also becomes sensitive to temperature changes during running, and the rollers would have to be made to extreme accuracy.

The N—N—2N arrangement is a stable arrangement which may be used over a limited range of reduction ratios. It will be noted that the outer row of planets are of two different sizes, the bulk of the output torque being transmitted from the larger ones, the smaller ones being used to give the necessary contact loading for the second and first row planets. This type is a little more difficult to design from the ring loading and stressing points of view, but it is still within the bounds of known text-book theory.

All three row drives have the planet cage output in the same direction as the input to the sun. The ratio obtainable is

$$\left[\frac{D_1}{D_2} \times \frac{D_2}{D_3} \times \frac{D_4}{D_5} \times \frac{D_6}{D_7}\right] + 1 - \text{sun to planet cage.}$$

(v) **Four row transmissions**

The planetary arrangements possible with this type follow closely the pattern of three row types, with an added row. Reduction ratios up to about 600:1 may be achieved, the planet cage output being in the opposite direction to the sun input.

General design consideration

(a) **Fatigue life**

When machine components are subjected to direct, bending or torsional stresses, providing the reversed stresses are kept below some critical level, the component may have " infinite " life. Unfortunately this does not occur when components are subjected to Hertzian (contact) stresses, there being a finite life for every level of stress reversal. However, the contact stress levels which may be imposed are generally much higher than direct or bending stresses, *e.g.* a steel having an ultimate tensile strength of 100 tons/sq. in tensile would probably stand over 300 tons/sq. in contact stress reversals for millions of cycles.

Design of planetary friction transmissions—especially for the high input speed types—must therefore be based on the stress levels which are applicable to the materials used and the life required. For determining levels readers are referred to Lipson & Juvinall[3]—" Handbook of stress and strength ", which gives average values of contact stress levels determined by several workers in the field, in relation to life.

(b) **Power transmission**

The power (torque) which can be transmitted is proportional to the normal load (P) between the rollers, the number of rollers (n) sharing the load, the diameter of the input roller (D) and the coefficient of traction which is applicable to the roller contacts. *i.e.*

$$\text{Input torque } T_1 = Pn \ \frac{D}{2} \ . \ C_T$$

The coefficient of traction is mainly dependent on the lubricant used, varying from about 0·03 for ordinary lubricating oils such as OEP 69, Tellus 33 etc., to 0·055 for special oils developed for this work such as Hydrotorque or 1842A etc. If the contacts were to be run " dry ", coefficients up to about 0·35 could be obtained, but it is unlikely that a satisfactory design could be produced to run in that state. The contacts when lubricated may be considered to be classical elastrohydrodynamic in nature, and a large amount of information on the theory of such contacts has appeared over the last few years—the text book by Dowson & Higginson[4] being a good general reference.

In the simple and compound epicyclic types of transmissions, loads imposed by the ring on the planets are transmitted directly to the planet/sun contacts. In multi-roller types however, there may be force amplification at some of the intermediate contacts—the design has therefore to be a compromise between contact stress at the intermediate contacts and fatigue life.

With designs so far carried out, the fatigue life of the outer rings with respect to the bending and compressive stresses imposed by hydraulic pressurisation, has not been a problem. The ring thicknesses may be optimised to give the lowest possible hydraulic pressure compatible with the loading required.

Experimental Designs

As mentioned earlier, to test the validity of a theoretical design, a simple epicyclic transmission was manufactured for tests[5]. This unit, employing hydraulic pressurisation of the outer ring, was designed to transmit 48 HP at 3,000 rpm input, to have a reduction ratio of $2\frac{2}{3}$:1, and a contact width of 1·0 in. The outer ring was 5 in. internal diameter, the sun roller 3·0 in. dia., and had six planets each 1·0 in. diameter. A photograph of the unit is shown in Fig. 7. The unit is approximately 7·75 in. outside diameter by 8·0 in. long over the stub shafts. In order to use materials readily available, the rollers and ring were made from normal case—hardened mild steel, the contact stress level being kept down to 80 tons/sq. in max. Plain bearings were used throughout to reduce noise. Manufacturing tolerances on the roller and ring

FIG 7. Epicyclic Transmission Unit.

sizes were arranged to give virtual " size for size " fitting on assembly.

Results of tests in this unit, using " Hydrotorque " fluid are shown in Figs. 8 and 9. Fig. 8 shows " slip torque " plotted against hydraulic pressure on the outer ring. Here, " slip torque " is defined as the torque which produces 0·2% slip through the unit, *i.e.*

$$\text{slip} = \frac{\text{Input rpm} - 2\frac{2}{3}\ \text{output rpm} \times 100\%}{\text{Input rpm}} = 0{\cdot}2\%$$

Assuming that there was zero clearance between the rolling surfaces initially the response should follow the " design line " shown in Fig. 8, passing through the design point at 48 HP. In the event it will be apparent that approximately 500 psi pressurisation was necessary to take up clearances, the response curve then following the design line slope very closely, being slightly non-linear. The initial design was based on a coefficient of traction of 0·05, from information gleaned from a number of sources. The apparent variation on this figure from the test results being from 0·048 to 0·053 over the power range shown.

Fig. 9 shows a number of plotted points of the transmission efficiencies taken at 2,500 psi pressurisation and 2,500 r.p.m. input. The full line is a theoretical curve assuming that the intrinsic losses due to bearings etc., remain constant at constant speed, *i.e.* losses not affected by power.

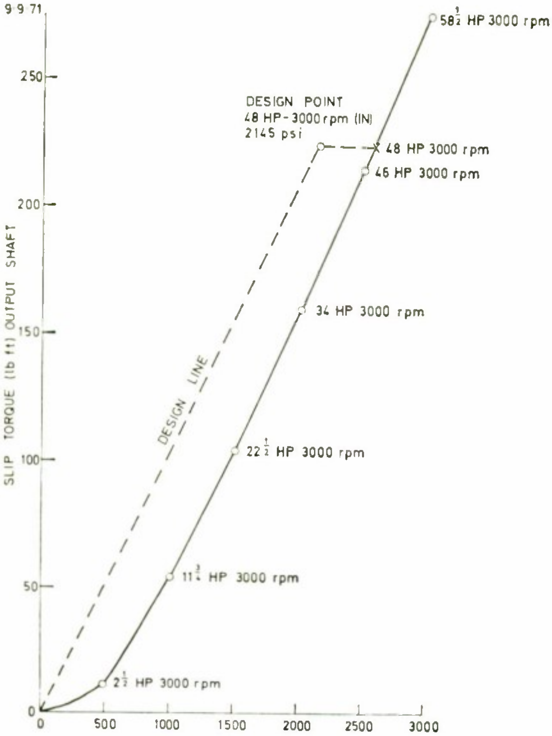

FIG. 8. Fixed Ratio Transmission Slip Torque with Pressure.

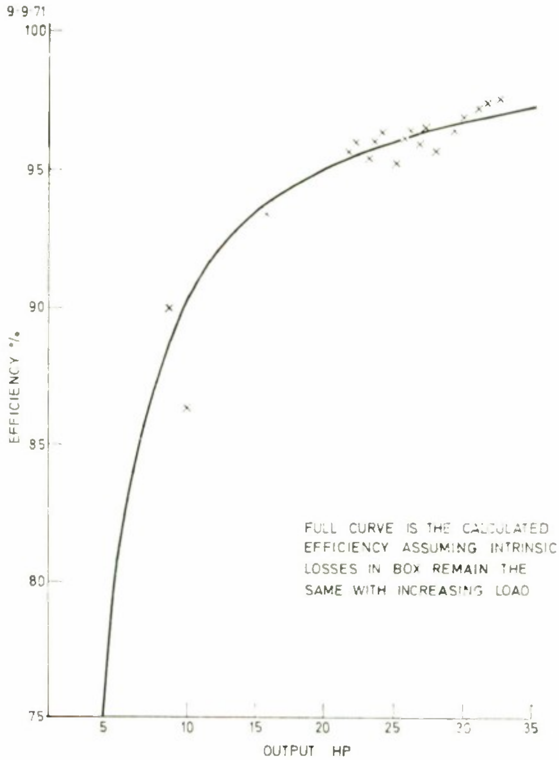

FIG. 9. Efficiency of Fixed Ratio Transmission Unit at 2500 psi and Input rpm 2500.

It is difficult, without building a comparable gear type transmission, to assess the noise and vibration characteristics of the planetary friction drive. Subjectively the noise output was found to be extremely low, in fact embarrassingly low, since noise generated by the drive motor, the loading dynamometer and couplings etc., were dominant.

The simple epicyclic transmission has however served its purpose in substantiating the theoretical design, and has enabled tests to be carried out on various lubricants to obtain parameters which can be used in future designs.

Two row transmission

Rolls Royce (1971) Ltd., have designed a two row transmission for AUWE to work in their closed cycle thermal power unit for torpedo applications. Since this unit is required for prolonged testing, the contact stress levels have been kept down to about 80 - 90 tons/sq. in. It is designed to accept an input of 130 HP at 31,000 rpm, to have a transmission ratio of 15·45:1 using Esso 274 turbo oil. The unit has an internal ring diameter of 7·783 in. and has five planets in each row (similar to Fig. 3). If this unit were designed for a maximum life of about 10 hours, which would be applicable to an operational torpedo, the ring internal diameter could be about 6·0 in.

Three-row transmission

The design of a three-row transmission [6] has been completed at ARL, and the units are about to be manufactured. These are intended to accept an input of 150 HP at 50,000 rpm, to have a reduction ratio of $33\frac{1}{3}$:1 with five planets in each row (N—N—N arrangement —Fig. 4). Two of these units will be tested in a back to back configuration. Additionally, a two row contra-rotating unit is being manufactured to split the output of the second unit into a contra-rotating pair.

An outline design of a further unit has been prepared which could be used as a step-up unit to drive a helium compressor at 200,000 rpm. This unit has an input of 100 HP at 3,000 rpm and 67:1 step up—ratio, being similar to the N—N—2N arrangement shown in Fig. 5. The ring internal diameter would be approximately 10·5 in., designed to give 6,000 hours life.

Future possibilites

There are probably many possible applications of planetary friction transmissions where high speed inputs, large reduction ratios and quiet operation are required. At the present time no limit to the powers which could be transmitted is evident, but running experience of units already in the "pipeline" is necessary to further development.

The possibilities of very high rotational speeds opens up the field of research into high speed phenomena in the area of contact stresses and oil film conditions, where gear type transmissions would be unrealistic.

References

(1) Algirdas L. Nasvytis—Multi-Roller Planetary Friction Drives—SAE paper 660763 (1966).

(2) W. E. Elford—Patent application No. 53751/71.

(3) Lipson and Juvinall—Handbook of Stress and Strength—New York. Collier-Macmillan Ltd., London.

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(5) W. E. Elford—The Design of Planetary Friction Transmissions (a) Simple Epicyclic Types ARL Design Note ARL/DR/M5.3/N1.

(6) W. E. Elford—The Design of Planetary Friction Transmissions (b) Multi-Roller Types ARL Design Note ARL/DR/M5.3/N2 (not yet published).

Organisation of Scientific Staffs in the Navy Department

As was announced in OM(GEN) 148/71, Mr. B. W. Lythall has been appointed one of the Deputy Controllers under CER (DCERA), while at the same time remaining a member of the Admiralty Board. It has now been agreed that under this arrangement Mr. Lythall will be responsible not only for acting as a link between the Board and the Procurement Executive but will also be available to give the Board general scientific advice and to exercise broad professional supervision of the work of the Naval Scientific Advisory Group referred to below. In his capacity as a member of the Admiralty Board Mr. Lythall will retain the title of Chief Scientist (RN).

Following the transfer of the bulk of the scientific staff of the Navy Department to the Procurement Executive, it has been decided that in order to provide scientific support to members of the Admiralty Board and their staffs a Scientific Advisory Group should be set up in the Navy Department under Mr. A. W. Ross who will be known in future as Deputy Chief Scientist (Navy) (DCS(N)).

Though working under the general scientific supervision of Chief Scientist (RN) the group will be part of VCN's department and the Head will report to VCNS. He will however also have direct access to other members of the Admiralty Board in recognition of the fact that the group is available to provide support for all Board members and their staff.

THE HEAT PIPE IN THE CONTEXT OF ELECTRONICS COOLING AND TEMPERATURE CONTROL

D. A. Reay, M.Sc.
International Research and Development Co.

Abstract

This article briefly reviews the more common techniques used for cooling electronic components and equipment, and lists the requirements of the equipment manufacturer and user in selecting cooling methods.

The heat pipe is one device which can meet many of these requirements, and its present status is discussed. The author also outlines the major properties of the heat pipe (including flat plate forms and a direct contact system), suggesting types of applications where these properties are attractive.

Introduction

The more familiar techniques used to aid heat dissipation from electronic equipment and components have progressed considerably over the past decade. This has been necessary to meet the increasing demands made on these systems by electronics and packaging engineers, both in terms of increased power generated by isolated components, and the closer packing densities required to satisfy overall size restrictions.

This progress has manifested itself both in developments in individual branches of heat transfer technology—the variety of aluminium finned heat sinks now available is much greater than in the early 1960's; and in " new " techniques. Of these, direct contact liquid cooling has probably received most attention, in the face of some considerable reluctance to accept such a system on the part of equipment users.

Types of cooling and temperature flattening employed in electronics may be divided into a number of classes. The major systems are:

(i) Free or forced convection air cooling applied directly to the component.

(ii) Free or forced convection cooling of a heat sink to which the component is attached, either to give extra area for heat transfer or to even out temperatures.

(iii) Liquid cooling.

(iv) Vapour cooling.

(v) Thermoelectric (or Peltier Effect) cooling.

(vi) Heat pipes and wick distribution systems.

There is inevitably much overlap between classes; for example liquid cooling is often applied to a solid heat sink where direct liquid contact with the electronics component is undesirable. Also heat pipe systems are generally used in conjunction with some extended surfaces remote from the component, enabling heat dissipation to the air to take place at a satisfactory rate. Other combinations are easy to identify.

Types of Cooling

Free and forced convection cooling

Convection cooling may be used either to remove heat directly from the components, or, where increased dissipation is required, *via* a heat sink. Here we are more concerned with applications where some aid to cooling, in the form of a heat sink or some other device as outlined in the previous section, is necessary.

The first applications for heat sinks were in cooling of transistors, when it was found that the surface area on the device itself was insufficient to keep the junction temperature below its permissible maximum. Typically, a transistor utilising only its package surface area for heat dissipation may have its cooling rate increased by a factor of three using a simple finned heat sink attachment.

The general method for presenting the characteristics of a heat sink is in terms of its thermal resistance, and is normally measured in degrees Celsius per watt. Heat sink thermal resistances vary greatly, very small units having values of the order of 50° C/W, those of large multi-finned power semi-conductor forced air cooled sinks being 0·1° C/W.

A second function of metal heat sinks is temperature flattening. By mounting a large number of transistors or ICP's on a block of copper or aluminium, some evening out of temperature can be achieved, ensuring that all the components operate under similar conditions. Heat may of course be dissipated from this block with the aid of extended surfaces.

Liquid cooling

Liquid cooling can take a number of forms. The electronic component or instrument may be immersed in a container through which a liquid is circulated, or a completely encapsulated unit relying on liquid agitation for heat transfer may be used. Alternatively the component may be attached to a simple solid heat sink which in turn is cooled by a circulating liquid.

Of the above three types of liquid cooling, the last is probably the most popular, avoiding as it does any contact between component and liquid.

Within the context of microelectronics cooling using liquids, a considerable amount of work has been put into the development of fluorocarbons, which have reasonable heat transfer properties while being almost chemically inert. They are also very resistant to electrical breakdown. One of the advantages of liquid cooling of microcircuits is the removal of local hot spots on a scale not possible with air cooling. The major drawback is that it involves direct contact with the electronic component. Apart from introducing problems during routine inspection and maintenance, encapsulation techniques must be well proven and any errosion caused by possible nucleation sites must be eliminated.

Vapour cooling

Vapour cooling of electronic equipment is closely linked to liquid cooling, particularly when direct contact systems are compared. Similar limitations on acceptability exist, but vapour cooling systems tend to be more complex than their liquid counterparts.

Vapour cooling has proved most attractive for high power devices, such as electron tubes, where flux densities are also high and the total heat generation may be measured in kW. Exponents of these systems claim that heat fluxes of the order of 200 W/cm^2 can be satisfactorily achieved by evaporation.

Thermoelectric devices

Thermoelectric, or Peltier effect, cooling, most commonly applied to semi-conductor devices, has been in existence for several years, but has always found a comparatively limited market, being most appropriate where very close temperature control or removal of isolated hot spots are the main functions of the cooling system.

The basis of a thermoelectric device is a P - N junction. At open circuit the device is simply a thermocouple; a temperature gradient maintained across the plates will cause a potential to appear across the terminals which is proportional to the temperature difference.

If the circuit is electrically completed through a battery or other DC source, it becomes simultaneously a thermoelectric heater and cooler, or a heat pump. By reversing the current the flow of heat may be reversed.

It is claimed that compared with other cooling methods, thermoelectric elements effectively increase the permissible heat dissipation, and do so with less additional mass and volume within the chassis. Its main advantage is in cooling an isolated component, where large heat sinks would be unnecessary. Heat capacities are fairly low, and the system needs a power supply.

Heat pipes and wick distribution systems

The heat pipe, shown diagramatically in its basic tubular form in Fig. 1, is a simple structure which exhibits a very high thermal conductance when compared with solid metals. For example a heat pipe having a diameter of 1 cm, able to transfer 100W over a distance of 30 cm at 150°C, has a thermal conductivity 400 times that of a copper bar of identical size.

First descriptions of this device appeared in 1964, although a patent was filed covering the principle by Gaugler of General Motors in 1942. Much of the early experimental work. and the associated development of theoretical analyses, was carried out at Los Alamos Laboratory, New Mexico, applications being concentrated in the field of thermionic power generation. Several laboratories in the United Kingdom are now studying the device in a wide variety of applications, including the cooling of electronic equipment.

High heat transfer capabilities are obtained within the pipe by evaporation of a working fluid, the selection of which depends partly on the required operating temperatures at the heat scource (evaporator).

The vapour travels to other sections of the container, and is recondensed giving up its latent heat of condensation, at a convenient remote part of the system, The unique feature of the heat pipe is the wick lining the inner wall, and this is used to carry the condensate back to the evaporator by capillary action. In this way, the heat pipe can operate against gravity (or in a zero-gravity environment) without the need for an external pump. (The wick also has other functions, which are discussed in subsequent sections.)

While the tubular heat pipe is a useful tool for many applications, flexible, flat plate, and combinations of all three with junctions in the form of wick or wall interconnections are possible.

Wick distribution systems are envisaged in which the heat pipe wall is omitted, and the wick brought into direct contact with the electronics component or module to be cooled. This would remove one of the interface resistances to heat flow.

Factors affecting the selection of cooling techniques

A large number of factors influence the selection of cooling techniques for both microelectronics systems, and units incorporating

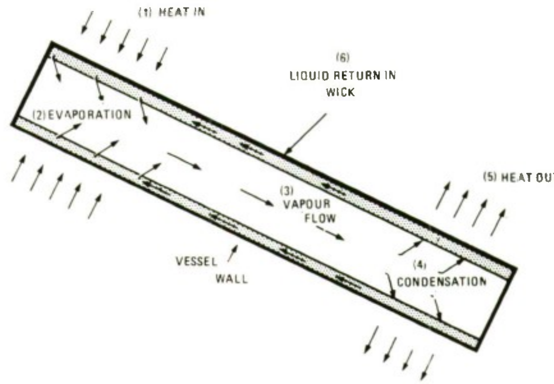

FIG. 1. The Heat Pipe Operating Cycle.

power semiconductors and large thyrister control circuits. The most important aspects governing the choice of the equipment manufacturer or user are listed below:
(i) Thermal efficiency, (ii) Cost, (iii) Weight, (iv) Simplicity, (v) Size, (vi) Reliability, (vii) Life, (viii) Thermal inertia, (ix) Availability, (x) Areas for heat rejection, (xi) Reaction of the manufacturer/user to the system, (xii) Maintenance and ease of replacement.

These factors may of course be further subdivided. In the case where a comparatively new technique is being introduced, and there is the possibility of a growing demand for access to this new technology, the significance of item (ix), availability, becomes a serious consideration.

The availability of the system encompasses such features as:

(a) Location of manufacturer(s)
(b) Manufacturing experience
(c) Number of manufacturers
(d) Development work required

As well as strategic considerations, where a manufacturer in the United Kingdom would be preferred, companies may require at least two sources of supply.

Before dealing with the ways in which the heat pipe might satisfy the requirements above it will be beneficial to outline the ways in which heat pipes could be used in electronics cooling.

The Heat Pipe in relation to Other Cooling Techniques

A description of the operating principle of the heat pipe has already been presented, and it is of interest to briefly consider the four main properties of the heat pipe, and to identify those which might be of value in the context of electronic cooling and current techniques.

The majority of heat pipe applications have been directed at taking advantage of one or more of the following properties of the heat pipe:

(i) Source/sink separation
(ii) Temperature flattening
(iii) Heat flux transformation
(iv) Heat flux control

If we consider the basic heat transfer function of a heat pipe, it reveals itself solely as an instrument for transferring heat between two points at a very high efficiency. This suggests its use in conjunction with, for example, finned heat sinks, for dissipation of heat remote from the heat-generating device. A heat pipe can, therefore, complement an existing cooling system, offering attractive new uses for this cooling system.

In most concepts utilising heat pipes, the interface representing the heat pipe wall is retained, although IRD have proposed alternatives, including the wick distribution system. This interface must be considered as a resistance to heat flow, and it is often the case that this cooling device will be compared with direct conduction to a liquid, with the heat pipe wall being given the status of a major impedance to heat input to the device. Two points must be remembered when making this comparison, however; firstly the wall thickness of a heat pipe is always kept to a minimum, consistent with structural integrity, secondly the heat flux densities which a heat pipe evaporator section is capable of handling are far in excess of those attained by conduction and convection within a direct liquid-cooled unit.

Vapour cooling comes closest, in principle and in heat flux capabilities, to the heat pipe. The heat pipe, of course, only differs in one detail from the thermosyphon, whose principle, sometimes in a less obvious form is part of many vapour cooling cycles; namely the inclusion of a wick to distribute liquid and return condensate to the evaporator. This detail is, however, unique to the heat pipe system, and offers singular advantages in several electronics cooling applications where removal of hot spots and response time are of prime importance. The phenomenon of evaporation and condensation as a means for efficient heat transfer, using latent heat, occurring as it does under near-isothermal conditions, leads inevitably to temperature flattening, and the wick, provided that it is of sufficiently uniform structure and thickness, in no small way contributes to temperature and flux flattening during the evaporation process, provided of course that no nucleate boiling is precipitated. By feeding condensate to those areas where it is most needed, hot spots at the evaporator can be effectively minimised.

Heat flux transformation and control are two properties of heat pipes which, within the present context, may be considered as incidental. A high flux at the evaporator may be dissipated over a large area of condenser section—heat flux transformation is an everyday feature of any cooling system, the heat pipe undertaking it somewhat more efficiently. Heat flux control, as opposed to temperature flattening, may be obtained with the aid of

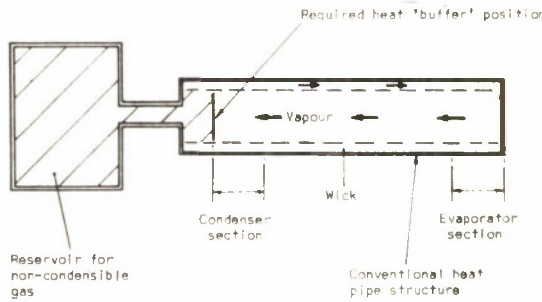

FIG. 2. Gas-Buffered Heat Pipe.

the gas-buffered heat pipe, in which a non-condensible gas is introduced into the condenser section. Variations in vapour temperature, hence pressure, cause changes in the volume of this non-condensible gas, opening up or blocking condenser surface area as necessary to maintain the system at a constant flux (Fig. 2).

Electronics Applications of Heat Pipe Systems

The prime attraction of the heat pipe in electronics cooling and temperature control is its effective thermal conductivity. As discussed earlier this is manifest as four main properties, two of which are of immediate relevance to electronics cooling applications. There are Source/Sink Separation and Temperature Flattening.

We may now consider the system geometry; this may for convenience be divided into three major categories, each representing a different type of heat pipe system:
(i) Tubular, (ii) Flat plate, (iii) Direct contact.

Tubular heat pipes

In its tubular form (with round, oval, rectangular, or other cross-sections), two prime functions of the heat pipe may be identified:

(i) Heat transfer to a remote location
(ii) Production of a compact heat sink

By using the heat pipe as a heat transfer medium between two isolated locations, recognisable applications become evident. It becomes possible to connect the heat pipe condenser to any of the following:

(i) A solid heat sink
(ii) Immersion in another cooling medium
(iii) A separate part of the component or component array
(iv) Another heat pipe
(v) The wall of the module containing the components being cooled

In applications where size and weight are needed to be kept to a minimum the near isothermal operation of the heat pipe may be used to raise the temperature of fins or other forms of extended surface. This leads to higher heat transfer to the ultimate sink medium, commonly air, and the advantage may be used to uprate the device or reduce the weight and size of the metal heat sink. There are two possible ways of using the heat pipe here:

(i) Mount component directly onto heat pipe
(ii) Mount component onto a solid plate into which heat pipes are inserted

Flat plate heat pipes

The second of the three main categories of heat pipes likely to be most useful in electronics cooling is the flat plate unit. It is not envisaged that this will be used in the immediate future to cool very high power units, but its use for temperature flattening and cooling in association with the smaller semiconductor and transistor packages is not in doubt, nor is its application to integrated circuit packages. The applications of the flat plate unit may be summarised thus:

(i) Multi-component array temperature flattening
(ii) Multi-component array cooling
(iii) Doubling as a module wall or mounting plate

Flat plate heat pipes could also be used in conjunction with tubular examples.

Direct contact systems

Looking a little further into the future, IRD see advantages in certain applications in either removing the heat pipe wall, retaining the wick to ensure good liquid distribution and even heat fluxes, or mounting components within the wick of a " conventional " heat pipe system, with electrical connections through the heat pipe wall. A reservoir would be provided in the former arrangement to ensure continuous liquid feed to the wick(s). One concept is shown in Fig. 3, while sample heat pipes made at IRD, including a flat plate unit, are shown in Figs. 4 and 5.

Practical Systems—Status of The Heat Pipe

An earlier Section listed factors affecting the choice of cooling systems for electronic components and equipment. We are now in a position to consider the status of the heat pipe in the context of these requirements:

(i) *Thermal efficiency*

In terms of effective thermal conductivity, the heat pipe can be several orders of magnitude superior to equivalent solid metal conductors. In most applications conventional heat addition and removal considerations will be seen to limit performance, rather than the capacity of the device itself.

(ii) *Cost*

Initially heat pipe application studies are being directed at situations where existing cooling techniques are inadequate in terms of efficiency, size, or weight, and the user is prepared to accept heat pipes at some premium on cost. In mass production, costs should be competitive, provided one equates this to advantages of the heat pipe over other systems.

(iii) *Weight*

Heat pipes should offer weight advantages, although in many cases these are unlikely to be dramatic. Because of the high conductivity implying higher fin temperatures if dissipation to air is envisaged, less fin surface will be required.

(iv) *Simplicity*

The heat pipe operates by virtue of straightforward principles, and has no moving parts.

(v) *Size*

The heat pipe should offer size reductions.

(vi) *Reliability*

Provided that the extreme operating conditions of the device are fully appreciated by the heat pipe supplier and user, reliability criteria should be met over the expected life of the system (see also (vii)).

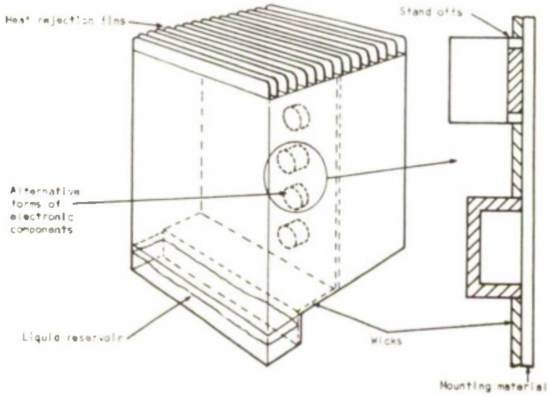

FIG. 3. Cooling Electronic Components by Direct Contact.

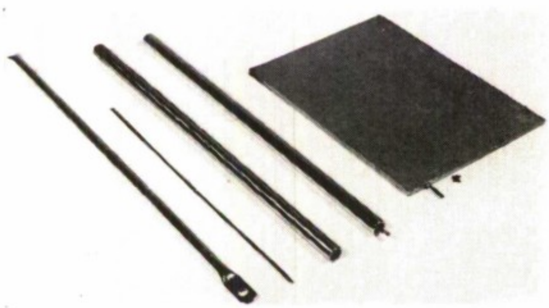

FIG. 4. Tubular Heat Pipes and a Flat Plate System made at IRD Diameter of the Smallest Pipe is 3 mm.

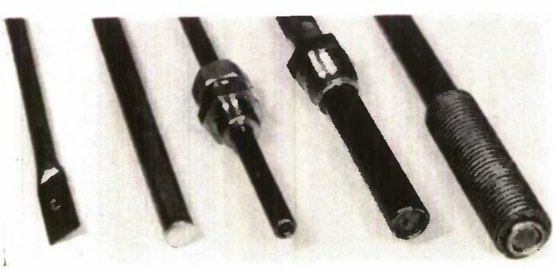

FIG. 5. Various End Fittings on Heat Pipes made at IRD for National Engineering Laboratory.

(vii) *Life*

The life of a heat pipe is governed by external and internal conditions. The most important single item is the compatibility of the working fluid with the wall and wick. At temperatures likely to be encountered in electronics cooling, heat pipe lives have been measured in years, and accelerated life tests equivalent to 20 year lives have been completed without degredation in one material/working fluid combination.

(viii) *Thermal inertia*

The reaction of a heat pipe to a change in evaporator temperature, provided of course that this change is kept within design specifications, is fast. Start-up of heat pipes from the cold is measurable in seconds, and reaction to small temperatures changes during operation at the design condition is even faster.

(ix) *Availability*

Heat pipes as well as being made in America are available in prototype form from IRD, and IRD would also undertake limited production runs. A manufacturer is being established, and units will be available during 1972 in considerable quantities. Heat pipe R & D in Britain is growing in many fields, and several companies have some experience in heat pipes for cooling electronics.

(x) *Areas for heat rejection*

Heat rejection in existing electronics is generally carried out in comparatively close proximity to the device being cooled. The heat pipe offers a simple solution to problems created by this, by connecting the device to a remote sink.

(xi) *Reaction of the manufacturer/user*

A process of education and familiarisation should lead to wide acceptance of the heat pipe system as a potential solution to cooling problems.

(xii) *Maintenance and ease of replacement*

Except in direct contact systems, maintenance of equipment cooled by heat pipes should present no great difficulty. Replacement of a combined heat pipe/device system may in some cases be easier than solely changing the electronic component(s).

Summarising, the heat pipe offers, to a varying degree, advantages which should prove attractive to equipment manufacturers and users. Of particular importance is its basic property, expressed as a very high effective thermal conductivity. This leads to weight and size reductions when compared with conventional heat sinks, and of course brings with it a " bonus ", the possibility of remote sink location.

THE FATE OF OIL SPILT AT SEA

M. Freegarde, B.Sc., A.R.I.C., R.N.S.S.
Admiralty Materials Laboratory

Michael Freegarde joined the R.N.S.S. as a Scientific Officer at Bragg Laboratory, Sheffield in 1956 after obtaining a B.Sc.(Hons.) in Chemistry and A.R.I.C. He carried out research into new methods for the analysis of steels and non-ferrous alloys, and was promoted to Senior Scientific Officer in 1962. He transferred to A.M.L. in 1966 and was promoted to Principal Scientific Officer in 1969. At present he is Head of the Inorganic and Physical Chemistry Section and is engaged on the application of sensitive analytical techniques to a variety of naval problems.

On a foggy night in 1966 the Norwegian tanker *Ann Mildred Brovig*, en route to Hamburg with 40,000 tons of Iranian crude oil, was in collision with a British coaster. On fire and leaking badly, the tanker drifted and stranded the next day on a sand bank. Some oil was eventually salvaged from the two halves of the remaining hull, but the bulk had already spread on to the sea and was drifting towards Scandinavia, where hasty preparations for its reception were being made along the threatened coastline. However, after several days of anxious watching, the slick, of some 20,000 tons, disappeared overnight. No satisfactory explanation has yet been offered.

In addition to major spillages of this type, of which on the average ten occur every year in the English Channel and its approaches, spillages from normal tanker operations amount to 100,000 tons per year being released into British coastal waters(1) and while in the long term the relentless ecological erosion brought about by small concentrations over long periods may be the more important aspect, major spillages attract the greater attention. An instance of the latter was the direct stimulus to the first major investigation dedicated to studying the fate of an oil slick at sea. The Zuckerman Committee, in reviewing the *Torrey Canyon* incident, listed nine areas where research was required. While most of these dealt with methods of treating the oil (by sinking agents, booms, detergents, etc.), a question was posed about the fate of the oil if none of these treatments were carried out.

This item—the effects of natural factors on the movement, dispersal and destruction of oil at sea[2]—was allotted to the Navy Department who had earlier investigated the delayed effects of the *Torrey Canyon* spillage. A working party was formed by DR/Mat 1 in 1968 to initiate, organise and co-ordinate relevant research for a period of three years. The purpose of this article is to describe some aspects of this research.

Some possible changes that can occur when crude oil is deposited on the sea are as follows. At first the oil will spread rapidly to form a thin homogeneous slick. At the same time, evaporation will take place (25-30 per cent in the first day) so that the oil remaining becomes increasingly richer in the less volatile components and so more viscous. The rates of spreading and evaporation therefore decrease. Depending upon the type of oil and the roughness of the sea, some emulsification will take place. Initially, effects such as dissolution and chemical and biological actions are expected to be small but, as the slick spreads out, these effects will be correspondingly accelerated, although their absolute rates may still be slow.

Subsequent changes will depend on the proportions of oil converted to water-in-oil and oil-in-water emulsions. The former are produced when water becomes entrained with viscous oil by wave action. The water content may increase to 70-80 per cent, giving the so-called "chocolate mousse". Chemical and biological reactions in the material are likely to be slow because the surface area open to attack is relatively small. On reaching the shore, the chocolate mousse will pick up sand and debris and the water will evaporate to leave tarry lumps in which further degradation will be very slow indeed.

True oil-in-water emulsions may be formed because of the presence of natural emulsifiers or by the application of detergents. In the absence of artificial treatment, it is likely that the bulk of the oil in a dispersed form will exist as relatively large droplets formed by agitation of the waves. In still water these droplets would coalesce to reform a slick, but in disturbed water, the droplets will be dispersed through a large volume of water. Separation will then be slow and the large surface/volume ratio of the oil droplets will permit other forms of attack. Sufficient solar radiation will penetrate the upper layers of the sea to make photochemical reactions possible. The oil may undergo chemical degradation as a result of bacterial attack; it may be ingested by filter-feeding organisms present in plankton; or it may simply stick to plankton, other marine life or debris and become distributed even more widely.

The foregoing aspects have formed the basis of the investigations carried out by the Navy Department.

Movement of the Oil Slick

Knowledge of the way an oil slick moves on the surface of the sea is of importance in the context of providing warning of shoreline pollution and of forecasting the probable life of the slick in the light of prevailing meteorological conditions. A prediction technique and the machinery for operating it have been established. For major slicks in the open sea the responsible body is the Department of Trade and Industry, acting through the Principal Officer of the Marine Survey Office of the area concerned, who will consult Maritime HQ, Plymouth, or Pitreavie, as appropriate. The prediction service will be provided by the Fleet Weather Centre at CINCFLEET, Northwood. For slicks that pose an immediate threat to the coast, and in confined waters, the responsible body is the Department of the Environment, and the prediction service will be provided by the Meteorological Office, Bracknell, and local outstations.

The prediction technique used by FLEETWC is to evaluate a vector $\overline{M}$ at say hourly intervals and sum over the period of the forecast. $\overline{M}$ is equal to the sum of the wind vector, $\overline{W}$, the tidal stream vector, $\overline{T}$, and the residual current vector, $\overline{R}$. $\overline{W}$ is in direction parallel to the surface isobars and in magnitude equal to 3·3% of the surface wind speed. The choice of 3·3% is largely empirical and gives a reasonably good hindsight fit to the observed movement of several large slicks in the open sea in the vicinity of the British Isles. Furthermore, it lies in the middle of the range of values suggested in the literature, which extend from 2·5% to 4·2%. The relative importance of $\overline{W}$, $\overline{T}$ and $\overline{R}$ depends on the circumstances —with a slick close inshore in a light wind, $\overline{T}$ will be the most important factor; but in the long term and in view of the cyclic nature of $\overline{T}$, $\overline{W}$ will be the most important. $\overline{W}$ is evaluated from actual and forecast isobaric charts and from observations from ships in the vicinity of the slick.

The performance of the technique has been evaluated in recent oil spills and from hind-casts of older incidents. The broad conclusion is that in the open sea the performance is normally good but close into land quite large anomalies can occur. Failure of the method can generally be attributed to the absence of reliable wind data on a sufficiently local basis and more rigorous tests of the prediction technique await improved meteorological fore-casting.

Spreading

The sudden release of a quantity of oil on to a water surface results in the oil spreading at a rate that is dependent upon gravitational forces, surface tension and viscous drag. The interaction of these effects can be computed for pure materials on still waters, but crude oil is a complex mixture and attempts to predict rates of spreading on the open sea have met with little success. An empirical relationship that assumes the instantaneous rate of spreading to be dependent upon the prevailing slick thickness has been proposed by Blokker[3]. The main value of the experimentally determined proportionality factors for different oils is in putting the oils in an order of spreading tendencies.

Fay[4] has shown that after the first hour or so after release, the oil has spread to such a degree that gravity ceases to have a significant effect and that further spreading depends upon the balance between viscous drag and surface tension. The oil is of course changing in composition all the time and this affects the overall surface tension, etc. Many observers of slicks on open water have commented upon the separation that occurs in the slick—the bulk of the oil spreads slowly but is surrounded by a rapidly expanding film which is only a few microns thick.

Berridge *et al*[5] have studied this fractionation phenomenon and have shown that it is more pronounced with some crudes, such as Brega and Tia Juana, than with others. This rapid spread or flash is attributed to the reduction of the surface tension of the water-oil boundary by the migration of surface-active components present in the oil. Subsequent dissolution of these compounds allows the associated oil to coalesce into droplets of microscopic size which, on account of water movement, will be dispersed and disappear.

A further factor that affects the spreading of the central core of the slick is the conversion of oil into a water-in-oil emulsion that may be quite rigid. This ultimately breaks up and becomes scattered by wave and wind action.

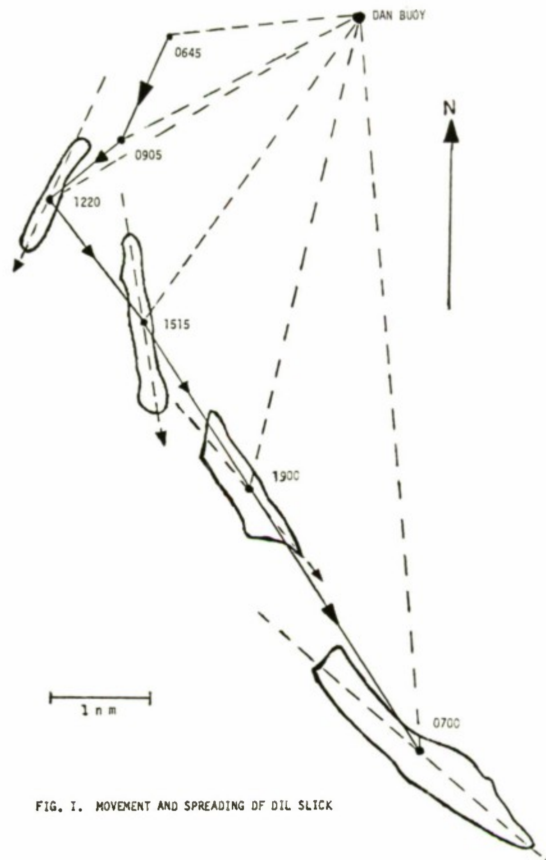

FIG. 1. MOVEMENT AND SPREADING OF OIL SLICK

An attempt to examine the spreading of an oil slick on the open sea was made during a trial in May 1971 when 100 tons of Kuwait crude oil were discharged in a position in the western approaches. The shape of the resultant slick was plotted from radar observations of a helicopter as it flew round the boundary, and its growth over a period of 24 hours is illustrated in Fig. 1. Not only is the slick spreading and changing its direction of movement, but also it changes its orientation, presumably as a consequence of local variations in current associated with tide and wind movements. The area of the slick at various times was calculated from the radar plots and photographs taken from the helicopter were also used (see Fig. 2). The increase in area was found to be approximately linear over the period of observation, a mode of behaviour not predicted by any of the theoretical treat-

ments considered so far. By the end of the day there were indications that the very thin film surrounding the thicker core of emulsified oil was beginning to break up.

In general, it would seem that the hydrostatic and surface tension forces that control the spreading process under laboratory conditions are on the open sea dominated by wind and wave action. As a result, in laboratory spreading experiments the film of oil remains largely homogeneous, whereas a slick at sea takes the form after a few hours of a comparatively small core of emulsified oil surrounded by much greater areas of very thin oil. The extent of this latter film is generally recorded as the area of the slick: the central core expands very little.

FIG. 2. Crude oil on the sea.

Solubility and Dispersion

The solubilities of the lighter n-paraffins in fresh water are roughly proportional to their vapour pressures. This relationship is expected to apply to the higher hydrocarbons also because both solubility and vapour pressure of a particular component are, for a homologous series, simply related to chemical potential in the mixture. A similar relationship will apply in sea water, although the absolute values of solubility will be lower. Thus the lighter components of an oil that are most rapidly lost by evaporation will also be the ones most subject to loss by leaching.

The logarithms of the vapour pressures of n-paraffins in the range C5 to C16 are proportional to their carbon numbers and extrapolation can be used to estimate the vapour pressures of the higher members of the series. At the start of this investigation, solubility data was not available above C8. However, the relationship between vapour pressure and solubility for light components was expected to hold and rough estimates of the solubilities of the higher components in fresh water were made[6]. Although the solubility of components other than n-paraffins is somewhat greater for a given carbon number, for the purpose of assessing order of magnitude solubilities these differences were neglected. The resultant approximate solubility data suggested that the true solubility of the kerosine fraction might be significant, but that true solution of the lube oil and higher fractions would be quite negligible (*e.g.* a saturated solution of C23 would contain 100 g km^{-3}).

Some experiments were carried out to test these predictions[7]. Firstly the solubility of decane was measured. This fell into line with prediction and so provided a more confident basis for extrapolations. A second experiment consisted of measuring the solubilites of some light components of crude oil in admixture in a commercial oil. The purpose of these measurements was to check the general application of Henry's Law in such a complex mixture. As a result, the extrapolated solubilities of the major crude oil fractions were revised a little and are given in Table 1.

TABLE 1.

Extrapolated Fresh Water Solubilities of n-paraffins in Heavy Fractions of Crude Oil

Fraction	Carbon Nos.	Extrapolated solubility in fresh water of corresponding n-paraffins, gm^{-3}
Kerosene	C10-C17	2×10^{-1} to 10^{-4}
Gas oil	C16-C25	3×10^{-4} to 10^{-8}
Lube oil	C23-C37	10^{-7} to 10^{-14}
Bitumen, etc	>C37	$<10^{-14}$

Although loss of the most objectionable crude oil fractions by true solution could be discarded, the formation of fine dispersions needed careful consideration—a suspension containing one part per million of oil dis-

tributed over an area of one km^2 to a depth of one m amounts to one ton of oil. To determine the stability of such suspensions, small volumes of oil were agitated with large volumes of water and allowed to settle. Samples of the aqueous phase were withdrawn after increasing periods of settling and the overall "solubility" of the heavier fractions was measured by spectrofluorimetry[8]. Typical results obtained with Kuwait crude oil are shown in Table 2. It will be observed that residual fine dispersions containing about 1 ppm of oil can persist for several weeks. It seems therfore that in a choppy sea significant amounts of oil could remain dispersed long enough to be carried quite deep, and if subsurface currents were favourable, it would then be distributed far beyond the confines of the original slick. This kind of mechanism may go a long way towards accounting for the disappearance of slicks such as that from the *Ann Mildred Brovig.* Wide dispersal would increase considerably the possibility of immobilisation by plankton, as described in a later section.

TABLE 2.
Rate of Separation of Crude Oil Dispersions in Sea Water

Time of Settling (days)	0·01	0·04	0·33	1·0	2·2	147
Oil Content (ppm)	31	4	3	5	3	0·6

Overall, it was concluded that dispersion formation could lead to the disappearance of large amounts of oil, but that loss by true solubility would be unlikely to affect any but the lightest components.

Supporting evidence for this view has heen ohtained from recent measurements of the concentrations of oil heneath a slick at sea[9]. The main problem was to devise a simple method of sampling without contamination by the slick or the accompanying ship. Knudsen marine sampling bottles were lowered in clear water to a greater depth than that from which samples were to be taken, and the ship then steamed slowly into the slick. At the chosen position, the bottles were raised so that the uppermost one was one metre below the surface and a messenger was sent down the wire to effect closure. All bottles were then lowered again and the ship moved to clear water before the bottles were taken inboard. The contents of each bottle were then transferred to glass bottles together with several washings with cyclohexane. The glass bottles were sealed and returned to the laboratory for determination of oil content by spectrofluorimetry.

The results of one trial are shown in Table 3. The wind was light (3 - 12 knots) and variable, and the sea calm. Nevertheless for substantial periods detectable amounts of oil were present. If during these periods an average value of 0·1 ppm is assumed for the uppermost 5 m of water beneath the slick, the area of which was about 10 km^2 at this time, the quantity of oil dispersed would be about 5 tons, a substantial proportion of the original 100 tons released.

TABLE 3.
Oil Concentrations Under a Slick.

Time after release (hours)	Depth of Sample (m)	Oil Content (ppm)
1	1	<0·01
	10	0·02
7·5	1	0·26
	5	<0·01
8·7	1	0·45
	5	0·11
11-12	1	0·01
25·8	1	<0·01
	5	<0·01
26·2	1	0·01
	5	<0·01

Water-in-oil Emulsions

The importance of water-in-oil emulsions lies in their ability to survive for long periods of time, resisting biological and chemical attack and eventually stranding, losing water by evaporation and becoming tarry lumps. The rapid uptake of water by crude oil floating on the sea has been demonstrated both in sea trials and in semi-field trials on a raft in Langstone Harbour. Kuwait crude oil formed an emulsion containing 40% of water in 2 - 4 hours, 60% in 12 hours and 70 - 80% in a day. Berridge *et al.*[10] have examined the formation

and stability of emulsions or " mousses " and have shown that the ease with which they are formed and thc stability they acquire varies with the type of oil, being related primarily to chemical composition. Some mousses were found to be stable for many months on exposure to the weather, while others were readily broken down and dispersed. The authors state that stabilisation of this type of emulsion appears to depend upon complex components of the non-volatile residues. Asphaltenes in particular and possibly porphyrins may well be responsible. Distillates from gasoline up to heavy lubc oil either did not form emulsions or formed fluid emulsions that existed only temporarily.

In an attempt to shed some light on the reasons for emulsion formation and stability, research contracts have been placed at Manchester and Nottingham Universities. A possible long term outcome of this work, which has a further two years to run, is that a thorough understanding of emulsion formation will facilitate the formulation of emulsion-breaking treatments.

The Effect of Sunlight

In the presence of air, the main chemical reactions undergone by crude oils are likely to be oxidation reactions, initiated either thermally or by the absorption of light. Air oxidation of paraffins, non-conjugated olefins, and many aromatics proceeds by a free radical chain reaction(11) and is auto-catalytic. The reaction is initiated by free radicals produced by the decomposition of impurities or by the absorption of light. The reactions can then proceed at an increasing rate because the products of the reaction (hydroperoxides) themselves decompose with the formation of more free radicals. The rate at which the reaction proceeds in a particular system is also governed by the presence of inhibitors, *e.g.* sulphur compounds, that act as terminators of chain reactions.

The hydroxy compounds formed by decomposition of hydroperoxide may undergo further dehydrogenation and peroxidation to yield aldehydes or ketones and ultimately carboxylic acids of lower molecular weight. On the other hand, products of higher molecular weight may be formed by radical-radical combination, by condensation of aldehydes or ketones with phenols, or by esterification between alcohols and carboxylic acids. For example, the gum produced in degraded gasoline consists largely of esters of higher molecular weight, while the degradation products of lubricating oils contain acids, alcohols, esters and carboxyl compounds(12). Products of lower molecular weight containing water-solubilising groups will be more readily leached from the slick and their formation will reduce the pollution hazard. Products of higher molecular weight are likely to form viscous gums or tars and would thus be expected to resist further attack and hence increase the pollution hazard. The object of the experiments conducted at AML(13) was to determine which types of products predominated and the rate at which the reactions were likely to proceed in sunlight.

Thin films of oil immersed in aerated fresh water or sea water were exposed to light filtered from a mercury lamp. In fresh water, with light of wavelengths shorter than 300 nm (*i.e.* shorter than the ultra-violet limit of sunlight), the photo-oxidation was found to be rapid. To assess the effectiveness of different wavelength regions, selected liquid filters were used. The products identified were carbon dioxide, acetic acid, sulphuric acid, and benzene-soluble organic acids and esters. Infrared examination indicated the presence of carboxyl and hydroxyl groups in benzene-soluble material and ketones and alcohols were probably present, but their amounts were unknown.

An assessment of the proportion of oil converted to water-soluble or volatile products was made using the simplifying assumption that these products consist of carbon dioxide and acetic acid only. On this basis, the rate of destruction of oil (CH_2) was calculated for each condition of radiation used, combined with the measured intensities of illumination to provide quantum efficiencies for decomposition, and, in conjunction with the spectral distribution of sunlight at the earth's surface, used to provide measures of the rate of decomposition to be expected in sunlight. The total rate or decomposition corresponded to the destruction of a 2·5 micron thickness of floating oil per 100 hours, or about 2·5 tons per km^2 per day. This applies to slicks of 0·1 mm thickness; if the latter is reduced to 0·01 or 0·001 mm, the total rate of destruction falls to 0·5 or 0·1 of this value, owing to partial transmission of the longer wavelengths. Thus, if a 100 ton slick reaches an area of about 8 km^2 with an average thickness of about 0·02 mm, the rate of loss would be of the order of 1 ton per day.

Marine Life

The impact of oil on marine life at the sea surface and in the intertidal and sub-littoral zones has understandably received considerable attention because of the damage done by the oil and the possible economic consequences. In the present context, however, it is of interest to enquire as to what degree of interaction there might be in the open sea and particularly the extent to which marine organisms may play a part either in destroying or dispersing oil.

Analysis of plankton samples after the *Torrey Canyon* disaster indicated the presence of substances having fluorescence spectra similar to that of crude oil and corresponding to oil contents of 0·1 to 1·0 per cent of the dry weight of the plankton[14]. Microscopic examination showed that some specimens had small oily globules adhering to the surfaces of the body parts, and it was suspected that these globules were in fact crude oil which had become attached while the animals had been swimming through a fine dispersion of oil in the sea water. It was not possible at that time to identify the microscopic globules, nor was there unambiguous evidence that the planktonic animals had ingested oil droplets, because the fluorescence spectra, although similar to that of crude oil could conceivably have arisen from natural constituents of the plankton.

The copepods are the most important group of zooplankton and form the main food of many fish. They feed by filtering out food particles in the form of microplankton from the sea water, and clearly, if this process of filtration were entirely unselective, they would also filter out any oil globules that were present. There is a considerable amount of information available about rates of feeding and on the assumption that feeding is entirely unselective, this information could be used to derive a rough estimate of the maximum rate of consumption of oil under favourable conditions. However, there is some evidence that the feeding process is a selective one[15]. Thus the possibility of oil consumption by plankton turns on the question whether copepods and similar filter-feeding organisms are capable of distinguishing between palatable food particles and oil droplets which are presumably unpalatable. The object of the experiments described in this section was to attempt to answer this question, and to determine the fate of oil should it be ingested.

Live specimens of copepods and barnacle larvae (Nauplius phase of *Balanus balanoides*) were transferred to sea water to which had been added a culture of the diatom *Phaeodactylum tricornutum* and a fine suspension (2 - 10 ppm) of oil droplets containing a fluorescent tracer. After 18 hours at 10°C, live specimens and specimens of faecal pellets were removed and examined with the Spectrophosphorimeter microscope[16]. By excitation with an appropriate wavelength, it was possible to observe directly the fluorescent contents of the guts of the animals (without interference from the body walls). The fluorescence emission from a single globule could be isolated and its spectrum measured. The presence of considerable quantities of oil in the guts of the copepods and barnacle larvae and in their faecal pellets was thus demonstrated unambiguously[17].

The fact that the oil passes unchanged into the faecal pellets is of considerable interest. The faecal pellets sink and the ingested oil is thus immobilized within the pellet membrane, at least for a time. The extent to which copepods can contribute to the immobilization of an oil slick will depend on the amount of oil dispersed as fine droplets, the rate at which copepods sweep the water clear, and the number of copepods present.

Using the data in Table 4 for *Calanus finmarchicus,* it is calculated that the maximum rate of oil immobilization by this species could be about 0·3 g/m^3 of sea water per day. To achieve this rate, the concentration of dispersed droplets would have to be 1·5 ppm or greater. Such concentrations can persist for considerable periods (as has been shown earlier) and in a choppy sea they could become widely dispersed. Plankton uptake is likely to be most pronounced under such conditions. To give some idea of the magnitude of the effect on a slick, considering the maximum rate that would result in favourable circumstances, a shoal of *C. finmarchicus* at a population of 2,000 individuals/m^3 covering an area of 1 km^2 to a depth of 10 m could immobilize 3 tons of oil per day. Of course, the zooplankton cannot contribute directly to the destruction of an oil slick because the oil must first be dispersed by the action of waves and currents. However, at times of the year when they are plentiful, their faecal pellets may well form an important "sink" into which falls a significant proportion of that part of a slick that gets dispersed in the sea water.

Microbiological Degradation

Sea water contains naturally a wide range of bacterial species as well as moulds, yeasts and related organisms that can attack oil, but the importance of these micro-organisms in assisting dispersal and destruction of oil at sea and on shores is still difficult to evaluate with certainty.

Under confined conditions bacteria produce sufficient surfactants to assist in the dispersal of oil in sea water[18] but effects in the open sea are uncertain. Droplets of oil undergoing microbial attack tend to sink, even in the absence of silt, but the mechanism is not fully understood. It is generally assumed that the use of dispersants on oil at sea will lead to an increase in the rate of natural biodegradation, but experimental information is awaited.

TABLE 4.
Calculation of Maximum Rate of Oil Immobilisation by ***Calanus Finmarchicus***

Maximum population:	2,000/m^3
Maximum rate of water filtration per individual:	100 ml/day
Maximum rate of production of faecal pellets per individual:	300/day
Maximum weight of faecal pellet:	1·5 x 10^{-6}g
Assumed maximum oil content of one faecal pellet:	0·5 x 10^{-6}g
Calculated maximum rate of oil immobilasation:	1·5 x 10^{-4} g/day/individual; or 0·3 g/m^3 of sea water/day
Concentration of oil dispersion required to achieve maximum rate:	1·5 ppm

Each component of oil is a potential carbon and energy source for micro-organisms. However, the rate of degradation will depend upon environmental factors such as oxygen content. Under selected laboratory conditions almost complete degradation of some crude oils has been observed in two to three months. Degradation at sea will be slower and will be handicapped further by mousse formation. n-alkanes will be attacked first, for which certain bacteria are specific. Slower breakdown of aromatic and naphthenic compounds will occur. The principal pathways of crude oil degradation have been summarized[19]. Some fifty strains of bacteria capable of utilizing crude oil or individual hydrocarbons have been isolated from estuarine mud[20]. The degradation of Kuwait and Nigerian Light crude oils by a mixed culture of marine bacteria has been studied in the laboratory. Changes in bacterial population were followed by counting numbers and types of bacteria present. Growth occurred equally in both crudes. Compositional changes in the oil were followed by chromatography and it was shown that biodegradation of n-alkanes occurred although iso-alkanes remained.

The main factors governing bacterial activity are temperature, oxygen availability, and the concentration of nutrients such as nitrates and phosphates. Nitrates or sulphates can be used by some bacteria as substitutes for oxygen as hydrogen acceptors; this oxidation can proceed in the absence of molecular oxygen. However, this anaerobic procedure is normally much slower than aerobic processes. In general, the maximum rate of decomposition occurs only when oxygen is freely available, as would be the case in the upper layers of the sea, particularly in the photosynthetic zone.

While the effect of micro-organisms in destroying oil has yet to be quantified, it may well represent one of the final stages in the chemical transformation of hydrocarbons into soluble substances.

Discussion

It would be of interest to attempt to visualize the extent to which the various agencies considered could act in destroying an oil slick. However, this sort of assessment is made difficult because of the range of properties shown by different types of crude oil, quite apart from light oils and residuals—for example, the loss by evaporation under static conditions in the laboratory can range from 33% for Tia Juana crude to over 50% for Brega. Moreover, differing contents of asphaltic and waxy components will result in the residues behaving in different ways. On the basis of observation of the spreading of slicks of Kuwait crude, and of the analytical measurements made, it would appear that the greater part of the oil spilled is accounted for by evaporation and by spreading to an evanescent film, while the

remainder is in part dispersed in the water and in part left as a stable emulsion. The evanescent film and the dispersed oil will be subjected to photochemical oxidation, ingestion by marine life and microbial attack. The stable emulsion will break into small lumps that will accumulate marine debris and either sink or be driven ashore. In either event, degradation will be very slow.

Acknowledgments

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" The Effect of Some Chemical and Biological Factors on the Degradation of Crude Oil at Sea ", by C. A. Parker, M. Freegarde and C. G. Hatchard, Symposium on Water Pollution by Oil, Aviemore, Scotland, May 1970.

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VISCOELASTIC MATERIALS FOR VIBRATION DAMPING

E. T. Clothier, C.Eng., M.I.E.E., R.N.S.S.
Admiralty Materials Laboratory

Introduction

Compared with materials such as metals and ceramics the mechanical properties of polymers are highly dependent on temperature and time. The behaviour of the shear modulus of an amorphous linear polymer at constant rate of strain is shown in Fig. 1, where we can distinguish several distinct regions of mechanical behaviour, a glassy or hard region in which one or more secondary transitions may occur, a large transition from glassy region to rubbery region, a rubbery region and a region of flow. The associated damping factor or loss tangent which is defined as the ratio of imaginary modulus to real modulus is also shown as the dotted line and it is apparent that the large energy loss peaks are associated with large changes in modulus. Since we are concerned with vibration damping these loss peaks are the main regions of interest to us and it is important to know how they behave with temperature and strain rate (frequency) and how we can control or modify them so that the best use can be made of their high mechanical loss properties.

In view of their importance in vibration damping it is perhaps worth considering the behaviour of the transition regions. The flow transition is of course the process of melting when the polymer molecules move as a whole relative to each other. It is usually a fairly gradual process with polymers and the temperature range at which it occurs is highly dependent on the molecular weight of the polymer. In a low molecular weight material the rubbery plateau disappears or is very small, but above a molecular weight of about 10,000-20,000 there is sufficient entanglement to introduce a rubbery plateau. Cross-linking also has a marked effect on the flow temperature. The damping factor of course increases in the flow region but this is not always of much value as the modulus has decreased so that it is difficult to couple mechanical energy to the material. With most polymers an elastic component still remains when the material is in liquid form.

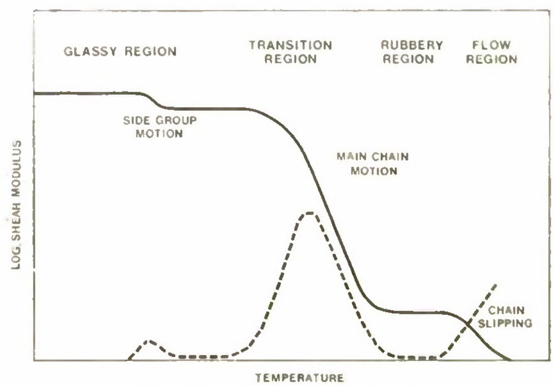

FIG. 1. Mechanical Behaviour of a Linear Amorphous Polymer.

The transition from the glassy to the rubbery region is often called the glass transition but this term is usually reserved for results obtained from dilation/temperature experi-

ments and sometimes measurements of deformation at very low rates of strain. Published values of glass transition temperature Tg are thus somewhat lower than temperature for maximum damping. This transition marks the onset of joint motion of parts of the main chain and is only affected to a small extent by the molecular weight of the polymer provided it is more than about a few thousand The modulus in this region falls by a factor of 1,000 times or more and is associated with a large peak in the damping factor. The main transition (and indeed other transitions) besides being dependent on temperature is also dependent on time or as we are concerned here with vibration it is probably more useful to describe it as being dependent on frequency. This molecular process is of course a rate process and has an associated activation energy. There is a relation between the dependence on temperature and the dependence on frequency and to some extent use can be made of this to predict material properties outside the range of those measured.

In the hard or glassy region there is usually (one or more) secondary transitions which are usually due to the freeing of pendant side groups or chains. The activation energy is less than that of the main chain transition and the shift with frequency is different. Secondary transitions thus often tend to merge with the main chain transition at higher frequencies and measurements must be made at about 1 Hz or lower in order to identify them.

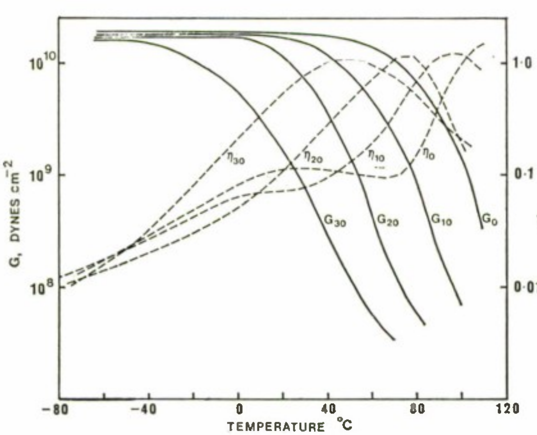

FIG. 2. Dynamic Mechanical Properties of Plasticised P.V.C. with 0, 10, 20 and 30% Plasticiser Content.

Materials Considerations There are various modifications which can be made to polymers at some stage in their processing to alter the mechanical properties to suit the operating conditions likely to be experienced in the final application.

(a) *Plasticisation*

Fig. 2 taken from Ref. 1 shows measurements of dynamic shear modulus and damping factor of PVC with various plasticiser contents as a parameter, it is apparent that plasticisation is a process by which the main chain transition can relatively cheaply be adjusted to a lower temperature with other minor effects. It is thus useful in materials which have a transition at higher temperature than desired, or are normally hard or glassy at the operational temperature. The radical change in dynamic modulus with plasticiser content can be partly explained by the effect of the plasticiser on some of the physical cross-links. PVC in particular has no chemical cross-links but a certain degree of physical cross-linking is present. The disadvantage with some plasticised polymers is that the plasticiser can sometimes slowly leach out with a consequent shift of the transition region. The effect of oil or water absorption by a polymer is often similar to that of a plasticiser on the transition region. A plasticising effect in some polymers can be achieved by flexible side chains which might be thought of as tied in plasticisers which should be less likely to leach out. Some materials using this technique are being currently evaluated at AML.

(b) *Flexibiliser*

These have been used with some success to make damping compounds based on epoxide resins. The principle is that of chain extension, *i.e.* the introduction of flexible sections into the main chain of the molecule. The technique is used to advantage in epoxides where most commercially available materials are of high stiffness. The advantage of the technique with epoxides is that if necessary the flexibiliser can be added when mixing the material on site and within limits a given transition temperature can be achieved by appropriate choice of the proportion of chain extender and hardener where the hardener introduces cross-links into the system. The materials resulting are relatively resistant to water and oil contamination. Although satisfactory materials for constrained layer damping at engine room temperatures

can be made using this technique, it has proved difficult to produce one for low temperatures although work is being done on this at the present time. Free layer materials for most temperatures can be made based on flexibilised epoxide resins.

(c) *Cross-linking*

Polymer molecules can be connected by primary valency bonds or chemical cross-links to give a three-dimensional network. An example of the effect of cross-linking on the dynamic mechanical properties of a polyurethane material in the transition region is shown in Fig. 3 from Ref. 2. As can be seen from the curves, with an increase in the cross-linking density the transition region moves to a higher temperature accompanied by a decrease and narrowing of the loss peak, there is also a marked increase of the modulus in the rubbery region. The impression is thus gained that from a damping point of view, cross-linking is a somewhat undesirable feature except in achieving a shift of the transition towards a higher temperature when some reduction in damping can be tolerated. However, it is important in many cases to have at least a limited number of cross-links otherwise the material may be unstable and unduly sensitive to water or solvents. Fortunately it appears that a limited amount of cross-linking has little or no effect on the damping properties of many polymers. Returning to Fig. 3, where the curve for the polyurethane with least cross-linking shows a wide loss peak and a very large fall in modulus almost down to 10^6 dynes/cm^2, the material associated with these properties in spite of the indication of viscous flow in the dynamic results was stated to have retained its solid shape up to 100°C. Only at cross-linking density of below 53% did the material exhibit cold flow at room temperature. (The cross-linking density is the quantity of curing agent used expressed as a percentage of the stoichiometric amount for complete reaction). Somewhat similar results have been noticed at AML with epoxies. It thus appears that with some polymers there is a narrow range of cross-linking density where a reasonable mechanical stability is retained while achieving maximum damping properties.

In addition to chemical cross-links it is also possible to obtain a similar effect by means of physical cross-links (Van der Waals forces or hydrogen bonding). These are reversibly broken by increase in temperature. It is noticeable that the modulus in the rubbery region of chemically cross-linked materials increases with temperature (Gough-Joule effect) while that of physically cross-linked materials decreases as the temperature increases.

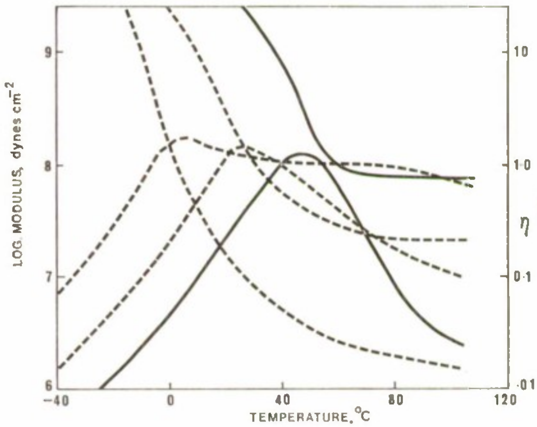

FIG. 3. Effect of Cross-Linking Density on Mechanical Properties of a Polyurethane.

(d) *Fillers*

To a certain extent fillers are used to cheapen polymers and indeed they can be important to this end, but in many cases they can considerably change with advantage the mechanical properties. In particular, free layer materials are rather ineffective unless the Young's modulus is considerably increased by the use of special filling materials. Nielson *et al* (Ref. 3) have given an approximation for the effect of a filler on the modulus:—

$$G = G_1 \phi_1 + A G_2 \phi_2$$

where G, G_1 and G_2 are the resultant shear modulus, the shear modulus of the polymer and the shear modulus of the filler respectively, ϕ_1 and ϕ_2 are the volume fraction of the polymer and filler respectively and A is an adhesive factor with a range of 0 to 1. In constrained layer techniques it is not usually necessary to effect as large an increase in modulus as in free layer damping, but it is often required to " match " the modulus of the material to the damping system. Further advantages are that of improving the mechanical stability and the introduction of thixotropic properties to materials where it is required to apply them to vertical or sloping surfaces. Some unfilled materials when cured do not bond well with adhesives but can be bonded if a filler is

present to act as a key for the adhesive. Disadvantages of fillers are that there is some reduction in the damping factor, sometimes accompanied by a shift of the transition to a higher temperature.

(e) *Co-polymers and Blends*

The question must be considered as to whether the use of a co-polymer or a blend of viscoelastic materials can give useful advantages. In general it can be said that certain compatible blends and co-polymers give a single transition while certain incompatible blends and block co-polymers can be arranged to give two separate transitions. Use can be made of this to give damping over a wider temperature range but at probably reduced effectiveness. Various equations have been given for predicting the glass transition of random co-polymers, for example:

$$Tg = \chi_1 \, Tg_1 + \chi_2 \, Tg_2 \ldots\ldots \text{(ref. 4)}$$

where Tg_1, Tg_2 and Tg are the glass transition temperatures of the two constituent polymers and the co-polymer respectively and χ_1 and χ_2 are the mole fractions of the two constituent monomers. It can be seen from the equation above that if it is possible to change the ratio of the constituents in a co-polymer or a compatible blend, a useful facility is available for moving the transition to any required temperature region between the temperatures of the individual polymers. Butadiene-acrylonitrile co-polymers are an example of this behaviour with certain limitations. The extremes are that of polybutadiene, a flexible rubber with a glass transition at about −85°C and polyacrylonitrile with a glass transition of about 103°C, while co-polymers are available commercially with a range of compositions vary from 18 to 45% acrylonitrile, which, with the appropriate choice of blend, can be used to give good vibration damping compositions having peak damping temperatures in the range −20 to +30°C.

(f) *Crystallinity*

Nothing so far has been said of crystallinity as this feature is invariably detrimental to high damping, the effect being somewhat similar to that of a high degree of cross-linking only more so. Fig. 4 from ref. 4 shows a comparison of the change of the modulus with temperature of a crystalline polymer compared with amorphous polymers with low and high cross-linking. The associated damping factor of the crystalline polymer is low.

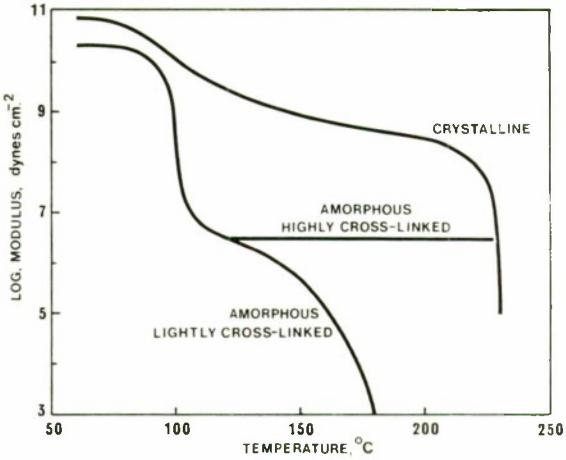

FIG. 4. Very Low Frequency Modulus v. Temperature for a Crystalline Polymer.

Application Techniques

Having considered what can be done with polymers, we can now enumerate the various basic techniques of damping and discuss the properties required from viscoelastic materials for each technique and what materials are available or how they can be achieved.

(a) *Free Layer Technique*

The free layer or homogeneous method dissipates energy in the extensional and compressional deformation of the viscoelastic material when the structure to which it is applied experiences flexural deformation. H Oberst (ref. 5) has given methods for estimating the damping of plates and beams with free layer materials. The mechanical properties required of a free layer material are those of high modulus and high damping, the product of which is the imaginary or loss modulus. As mentioned previously, fillers can give a useful increase to the modulus in the region where the damping is high and although there is a decrease in the damping factor associated with the addition of the filler, the result is a considerable net increase in the loss modulus. Although there might appear to be an amount of filler which can be used before diminishing returns are achieved, the limit is often determined by the maximum proportion of fillers which can be incorporated into the polymers. The highest modulus is obtained by use of anisotropic fillers such as flakes or platelets and in particular graphite flake has proved to be about the most effective cheap material although there may sometimes be electrolytic

corrosion problems when used with steel structures. An alternative less effective filler is flake mica. Fig. 5 shows the dynamic Young's Modulus and damping factor at constant frequency of a flake graphite filled flexibilised epoxy damping material. The damping of a structure using this material is sensitive to temperature and frequency and follows approximately the curve for the loss modulus but moves towards the damping factor peak for thicker layers. One disadvantage with a free layer is that large areas may be exposed to water or other contaminants.

(b) *Constrained Shear Damping*

The requirements for constrained shear damping are somewhat more involved. Besides a high damping factor, to obtain optimum results it is necessary to match the shear modulus of the material to that of the sandwich although to some extent the dimensions of the sandwich can be modified to suit the material. To achieve good damping over a wide frequency range on continuous beams the shear modulus should also be proportional to frequency. Unfortunately owing to the relationship between frequency and temperature dependence of viscoelastic materials, this could result in a system with a limited temperature range. In practice many useful materials have a shear modulus dependent on frequency to the power of about 0·4 to 0·6 which appears to be a useful compromise and may also be a more satisfactory figure in the case of certain stiffened structures. Fig. 6 shows the dynamic shear modulus and damping of a flexibilised epoxy suitable for constrained shear damping and Fig. 7 shows similar properties for Henley's compound (Yellow), the useful damping properties of which were first pointed out by J. Donaldson of N.C.R.E. This material is interesting in that it exhibits all the characteristics of becoming a liquid at higher temperatures or at lower frequencies but when used as a constrained layer damping material gives the same humped response as a more conventional polymer.

Viscoelastic materials in constrained layer damping are of course protected from the environment by the constraining layer and would not normally be expected to have to be so inert as free layers. However, the transition region is a characteristic of polymers which is particularly sensitive to ingress of some liquids and consequently this aspect cannot be ignored.

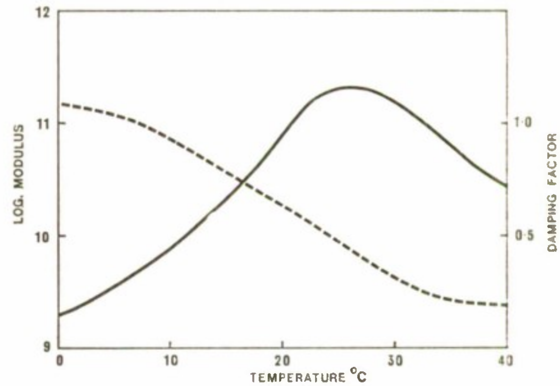

FIG. 5. Dynamic Young's Modulus and Damping Factor of EP36G50 at constant Frequency.
------- Log E. ——— Damping Factor.

We should not leave constrained layer damping without considering the constraining layer itself, in general it should be as stiff as possible within the weight penalty limits of the treatment and this can usually be achieved with steel. However, there are some cases, for instance when ferromagnetic effects are undesirable, when the use of a steel is not possible and examples of suitable alternative materials are boron reinforced aluminium and carbon reinforced epoxide resins which both have extensional moduli of the same order as steel.

(c) *Radiation Loading or Thickness Damping*

The possibility of effecting vibration damping by allowing the structure to radiate into a high loss medium which is closely coupled to the structure is worth considering. The properties required of the material in this instance are those which would give very low sound velocity in the material while giving fairly good match to the structure, *i.e.* high damping, relatively low stiffness and relatively high density. The use of this type of material to give thickness damping has been considered by Ungar and Kerwin[(6)] in which a form of thickness resonance is aimed at. The pertinent parameter for configurations with large lateral dimensions relative to the thickness is:

$$K = B + \frac{4G}{3}$$

$$\text{or} \quad K = \frac{(1-\nu)E}{[(1+\nu)(1-2\nu)]}$$

where B is the bulk modulus, G the shear modulus and E the Young's modulus and ν=Poisson's ratio. The bulk modulus is thus the most influential property.

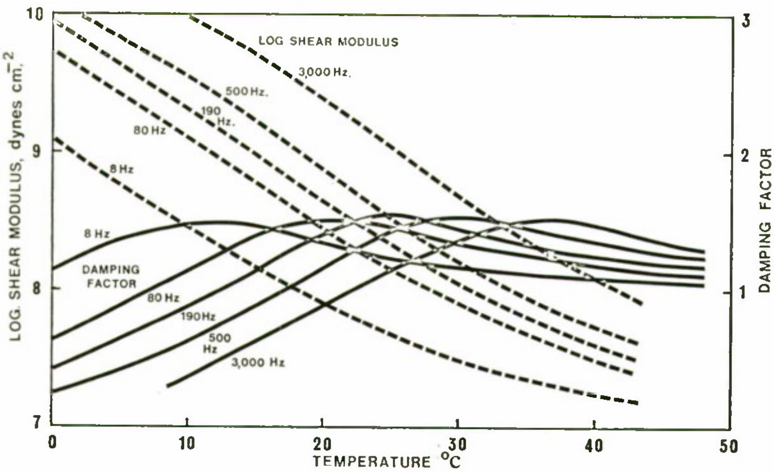

FIG. 6. Dynamic Mechanical Properties of EP71K100/50.

The above authors have given an approximate frequency at which maximum damping occurs for thickness damping:

$$F_1 \doteqdot \frac{(K'/\rho)^{\frac{1}{2}}}{4H_2}$$

where K′ is the real part of the appropriate modulus, ρ the density and H_2 the thickness of the layer.

The bulk modulus of a typical polymer material is of the order of 2 to 5 x 10^{10} dynes/cm^2. Consequently very large thicknesses would be required. The bulk modulus may however be drastically reduced by inclusion of air in the material in which case shear strain occurs around the cavities. Indeed, the material used in the experiment discussed in Ref.[6] must have contained entrained air probably carried in by the heavy filler. If there are no cavities of any form in the material, the strain is almost entirely governed by the bulk modulus with which little or no damping is associated. We have made a damping foam at AML which embodies the above principles and which can be injected into hollow box or similar castings or any structure which has a cavity which can be sealed off. The material can be introduced as a liquid by a foam dispensing machine and will foam and cure *in situ*. Little experience so far exists with this technique but maximum damping factors of 0·2 were obtained on small welded boxes made from ¼″ thick steel plate. The processing of this material does produce some unpleasant vapours which would be hazardous to health in confined spaces, although when cured the material is quite safe. It is hoped that a foam using less unpleasant constituents can be developed.

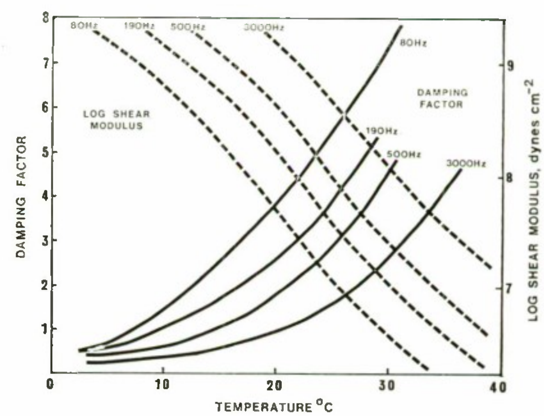

FIG. 7. Shear Modulus and Damping Factor of Henley's Compound (Yellow) A.P.No.E8/9231A.

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SHOCK AND VIBRATION TEST FACILITIES

C. K. Aked, A.M.I.E.E., R.N.S.S.
Admiralty Engineering Laboratory

Charles Kenneth Aked was educated at Pudsey Grammar School, Leeds; and Leigh and Southall Technical Colleges; joining the R.N.S.S. in 1947 at the A.S.E. Extension at Risley to work in the Radar and W.T. sections, and later the Quartz Crystal section. He moved to the Admiralty Engineering Laboratory in 1955, transferred from the Technical Class in 1958 to become E.O., promoted to S.E.O. in 1962 and took up the post of Works Manager (L) in the Electrical Department. From 1967 - 9 engaged in the development of "Quaver", returning to works management and took over the two posts previously held by the Works Manager (L) and (M). Interested in horology and historical research, and is currently Librarian and Curator to the Antiquarian Horological Society and also Chairman of the Electrical Horology Group.

Introduction

Many readers will be aware as a result of the Open Days held in July 1970 to mark the celebration of the Laboratory's Golden Jubilee that A.E.L. is the central establishment for the shock and vibration testing of equipment going into the Fleet. The shock and vibration facilities are available for use by all Ministry of Defence Departments, authorised contractors, and certain foreign countries. All work carried out other than for the parent department is of course on repayment.

Such work commenced at A.E.L. as a result of the unexpected experiences on H.M. ships during the first World War when the shock of a self-fired salvo was sufficient to disable a ship by causing the malfunctioning of electrical equipment and damage to filament lamps. Half a century ago the first shock test machine [1, 2] was developed at A.E.L., being an underblow machine using a one thousand pound pendulum suspended mass to provide known acceleration rates to lead-acid cells under test. Simple vibration machines were also developed contemporaneously to reproduce the structural vibrations[3] encountered in ships' hulls when under way.

Although operational requirements have resulted in increasingly severe specifications for shock and vibration tests on naval equipment, the basic principles remain. These are the scientific application of shock and vibration stresses to test items in order to monitor, record, and analyse the results of the applied stresses. Equipment which can withstand the tests satisfactorily will be reliable under service conditions.

It must be realised that the design of complex naval equipment to withstand severe shock and vibration conditions owes rather more to art than science[4, 5, 6]. The experts in the Shock and Vibration laboratory can tell at a glance whether an item is likely to pass or fail. Many optimists have watched with fond pride the installation of their brain-child on the A.E.L. shock machines only to see the remains swept into a bag for removal after the very first blow.

The purpose of this article is to convey some idea of the problems met with in the course of progressing a major works item and in the commissioning of new facilities. No discussion of the essential preparatory work in formulating proposals, obtaining financial approval, and the consequent insertion in the major works programme is made.

Preliminary Work

In 1962 the writer was instructed to prepare a suitable design for the construction of a Shock and Vibration laboratory at A.E.L. In spite of rumours of the transfer of A.E.L. to Haslar at an early date it was considered that if more than five years' service was obtained from the proposed new facilities then the project was viable since it was most important that the rate of shock and vibration testing be greatly increased if the requirements of the Navy were to be met. The site selected for the new laboratory (not by the writer) is shown in Fig. 1 as it existed in January 1963. It represented the last remnant of the very large pond that existed on the A.E.L. site for many years and probably resulted from the removal of the underlying brickclay and other works nearby. Why such a site should have been selected is a mystery. For many years it was used as an open soakaway for all the surface water drainage in the establishment and at one time was a stretch of water surrounded by banks of luscious reeds, nurtured it is said by strange chemical effluents discharged from the nearby Battery Testing bay. Shortly after the writer first visited A.E.L. the water level dropped rather dramatically by about six feet to the level seen in Fig. 1, possibly due to the very large building and civil engineering works in progress in the West Drayton area after the last war.

With the aid of the Navy Works Department (forerunners of the Ministry of Public Buildings and Works, now the Department of the Environment) trial borings of the proposed site were made, giving rise to local speculation that the Admiralty was drilling for oil. These trial borings showed that little disturbance of the ground below the depth of a few feet had taken place and the usual alternate layers of clay and gravel commonly found in this area were revealed. Indications were that the site was well suited for building purposes much to the disgust of the local pundits.

A scheme for diverting the surface drainage was evolved and shortly afterwards large deep holes appeared in various parts of the establishment to take large diameter open-ended concrete pipes installed vertically to form soakaways and to which the surface drains were connected, a major operation in itself.

FIG. 1. Site for the Shock and Vibration Test Laboratory, January 1963.

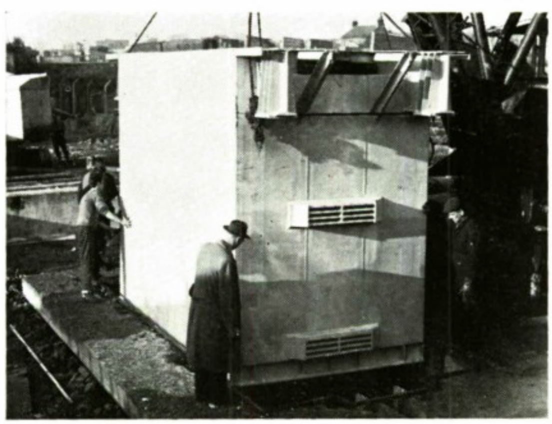

FIG. 2. Ballast Tank for the 2 tonne Shock Test Machine being lowered into its pit.

Because of the difficulties of access to the site certain buildings were noted for later demolition and others for future alteration in order to allow access to the new laboratory of the largest test items envisaged. Due to the congested main part of the establishment and consequent road restrictions it was also necessary to consider the delivery of test items *via* the rear entrance which necessitated its widening and consequent road alterations.

2 Tonne Shock Test Machine Pit

The main feature, and indeed the prime reason for the new building, was the inclusion of the 2 tonne shock test machine developed by N.C.R.E., a modified version of which was being constructed by the firm of Babcock and Wilcox on behalf of the Shock Panel for A.E.L. It was necessary for the civil engineering work associated with the installation to be carried out before the completion and delivery of the 2 tonne shock test machine itself, and, because of the large physical size, before the erection of the building. The drawing office of the Electrical Department of A.E.L. responded valiantly and rapidly produced working drawings of the huge concrete pit and foundation supports for the 2 tonne shock test machine, for whereas the N.C.R.E. machine had its table above ground level it had been decided to place the A.E.L. version at, or near, ground level in order to improve the accessibility for installation and test of equipment.

Work commenced on the site in January 1963 by driving metal piles into the ground to form a tank within which the reinforced concrete pit for the machine could be constructed. Due to a misunderstanding on the part of the contractor these metal piles were later found to be 6 ft. shorter than the length required and much to the writer's consternation the bottom edges of the piles appeared as the excavation reached the necessary depth. Warnings went unheeded and consequent upon a number of minor accidents the piles caved in. In order to re-start work it was necessary first to back-fill the excavation and re-drive the piles some 6 ft. deeper except the corner components which were left at the correct surface height to provide a datum level.

Although the contractor had been informed of the risk of water entering the excavation the site remained deceptively dry as the extremely cold weather at the time froze the soil. With an improvement in the weather the water entered with such a vengeance that the pit was completely filled overnight. From then on one or more pumps ran continuously day and night for many months to remove the thousands of gallons of water which entered each hour. Some of the wits of the establishment hinted that the level of the nearby Grand Union Canal was being monitored as it was suspected that unauthorised persons were removing vast quantities of water and thereby endangering navigation.

Eventually the pit was completed and the top of it may be seen in Fig. 2. The drainage sump for the pumping was sealed off by pumping concrete under pressure under the base of the pit. As the top edge of the pit was to be the datum level for the floor of the building it was checked from time to time when indications gave rise to suspicion that the pit was rising out of the ground. No doubt the influx of water on the cessation of pumping which resulted in the restoration of the normal water level to the site caused a large upward force to be exerted on what was virtually a large open concrete tank countered only by the resistance of the surrounding ground against the sides. However it was considered that when the ballast tank of the machine was installed and filled any movement would soon be negated. In the event this did not occur and the visitor to the Shock and Vibration laboratory has to enter by two steps instead of the designed level entrance.

Equipment Modifications Opportunity was taken at the initial planning stage to provide accommodation for all the shock and vibration equipment scattered throughout the establishment and which in the writer's considered opinion constituted unnecessary danger points to personnel totally unconnected with such work. For example the standard lightweight shock test machines[7] were situated in the open bays of the main shop and when tests were in progress workers were subjected to unnecessary and unexpected starts when the sudden loud noises occurred as the machines operated. One machine was actually situated where it was possible to walk under the raised hammer weighing 400 pounds! The largest vibration machine which was capable of vibrating a mass of 2 tonnes at up to 33 cycles a second was also placed in the open shop and although mounted

on a large concrete block insulated all round by a 2 in. thick layer of cork, nevertheless caused a great deal of damage to the main building by the transmitted vibration. The level of vibration in the structure may be judged from the situation where two officers sitting in an office sited on the upper floor and some 20 yards away had placed rubber blocks under the legs of the desks and chairs to reduce the effect of the transmitted vibrations. Even so papers and objects resting on the desks gradually drifted to the edges and fell to the ground. Immediately above the vibration machine area was the Instrument Repair and Calibration Centre and there was no need to tap the instruments under test when the vibration machine was in operation. Another unwanted effect was that machining operations on items in the workshop situated some 20 yards away were affected through the machine cuts being modulated at the vibration test frequency. Large cracks were caused in the substantial brick walls which however was to some extent caused as a result of an unexpected fault in the vibration machine discovered much later by the writer. It was also the practice to use the overhead block and tackle as a precautionary measure on large unstable objects being tested in order to prevent any danger of the item falling should a mount fail. The relatively small amount of vibrational energy transmitted to the building *via* the chains of the lifting block was sufficient to produce the most alarming effects.

The decision to accommodate the whole of the machines under one roof resulted in a great deal of design work for without exception each machine needed extensive modifications ranging from the relatively simple substitution of thyristor circuits for speed control of the drive motors for the small vibration machines in lieu of the former Ward-Leonard systems, to extensive electrical and mechanical alterations for the largest vibration machine and the Standard Lightweight Shock Test machines. It was decided to recondition each machine on removal and before re-installation. Theoretically such work was the responsibility of the Navy Works Department at the time but as they had no labour available and the expertise rested with A.E.L. in any case, there was little choice but to undertake the work from internal resources.

As originally fitted in its first location the 2 tonne vibration machine had several drawbacks. First the table level was over 3ft. from the floor level and it was very difficult to erect test items of large size on it because of the reduced headroom resulting. It was even more difficult to observe the effects of the vibration tests on the item. Platforms with supporting scaffolding had frequently to be erected and dismantled in order to allow observers and visitors to examine the test item and allow later removal. Another grave disadvantage was that the vibration machine amplitude and frequency controls were hand operated and mounted exceedingly low down, so much so that it was quite easy for a member of the shock and vibration test team to be recognised by the worn knees of his trousers. But the proposed change which caused the biggest headache was the decision to provide a means of isolation for the machine to prevent transmission of vibrations which might damage the new building and affect adjacent test areas.

A visit was paid to the Atomic Weapons Research Establishment at Aldermaston to inspect the shock and vibration facilities installed there in order to ascertain whether a suitable solution already existed although to no avail since the equipment in use was so radically different to that in use at A.E.L. The then Head of the Shock and Vibration section proposed the use of inflatable rubber pads such as those used on heavy commercial vehicles to isolate the 2 tonne vibration machine but after calculating the required mass of the concrete block on which the machine would be mounted opted out of the problem and it was then left for the writer to solve. No information on the proposed use of the inflatable rubber pads was available and therefore it seemed that the first point to check was whether the pads could actually carry the proposed loading. The concrete block, vibration machine, and balance weights to locate the centre of gravity of the composite construction under the geometric centre of the table of the machine would amount to approximately 35 tons in weight. Six inflatable rubber pads were available and therefore each pad would have to support approximately six tons. Since each pad had a projected support area of about 60 in. $\times$ 9 in. or 540 square inches, the inflation pressure to just raise the load would be 6 $\times$ 2240/540 or approximately 24 psi. So far so good and a practical test was all that was necessary to confirm it to be possible. Until that moment the writer had

not realised how difficult it was to find a six ton test weight in a suitable form. Fortunately the workshop supervisor, Mr. J. W. Nugent, suggested that it might be possible to utilise the Strain Cable Test machine used for testing cables at A.E.L. since it had arrangements to apply tension up to 10 tons on a test cable by means of a vertically arranged column of lead weights. One of the inflatable rubber pads was mounted in position on the cable test machine and by this means the application of the test load was made easy in the safest possible manner. Pressure tests using a very small compressor soon proved just how simple it was to lift up to 10 tons using one pad inflated with low pressure air. The air pressure was raised to the maximum rating of 60 psi to ascertain the performance and at this pressure slight distortion of the rubber walls of the pad became apparent so the test was brought to a close. A further precautionary test was carried out by raising the design load of six tons with an air pressure of approximately 30 psi and leaving an air pressure gauge connected to check the loss of pressure over 24 hours. No significant change of pressure resulted.

Suspension System

Fig. 3 shows the design evolved by the writer to raise the concrete block carrying the 2 tonne vibration machine clear of the concrete base foundation of the pit and thereby provide isolation to prevent the transmission of vibration to the foundations. It may appear complicated because of the number of components required to allow the system to be completely automatic in operation and hence minimise the mental effort on the part of the operator since he has quite sufficient to think about in connection with supervising the vibration test programme. As the writer had never previously designed an air system of any kind he was very pleased to locate a little book[8] published by Norgrens Ltd. which made it delightfully simple to calculate the parameters of the system. However as no one had previous experience of the behaviour of such suspension systems it was decided to have a " belt and braces " approach and have a 2 in. thick layer of cork slabs laid on the concrete base of the pit and under the concrete block in order to provide a measure of vibration isolation just in case of unforeseen difficulties arising.

Referring to Fig. 3, a small compressor pump feeds air to an air reservoir fitted with a pressure switch which starts the compressor pump motor when the air pressure falls below 80 psi and switches it off when the pressure rises to 100 psi. The compressed air from the reservoir is filtered to 25 microns, dehydrated, and the pressure regulated to 60 psi, all in a single combination unit which also drains off the accumulated water at intervals without attention. As the compressor installation is so small it is mounted in the corner of the pit together with the combination unit. A single $\frac{3}{8}$ in. outside diameter copper pipe carries the dry compressed air into the control console *via* a non-return valve. All the components to control and monitor the conditions in the suspension system, *e.g.* electrically operated solenoid valves, pressure switches, gauges, etc., are mounted within the control console. A manually preset pressure regulator is used to set the suspension system pressure at any specified level. Should pressure levels rise above the maximum set the over-pressure is sensed by a pressure switch which operates a relief valve until the air pressure falls to a safe level. In addition an electrically operated alarm sounds. All the electrically operated solenoid valves are fitted with air mufflers to reduce the noise when the air is released to atmosphere. From the console a single $\frac{3}{8}$ in. outside diameter copper pipe feeds into a ring main distribution pipe situated in the 2 tonne vibration machine pit from which the individual inflatable rubber pads which lift the concrete block are fed *via* two-way toggle valves and flexible hoses as shown in the small inset diagram of Fig. 3. The ring main is protected additionally by a mechanical over-pressure relief valve in case of failure of the console control circuits and any possible condensate is drained away by an autodrain unit. An electrically operated height gauge system gives the height of lift of the concrete block on a meter mounted on the control console panel, the maximum height of lift being two inches.

Once the suspension system has been set for the required pressure it will reach and maintain this indefinitely without attention each time the system is activated. Fig. 4 shows the control console for the 2 tonne vibration machine, the furthest panel being the control panel carrying all the controls and gauges for the suspension system whilst the two nearer panels carry the controls and meters for the variation of the amplitude and frequency of

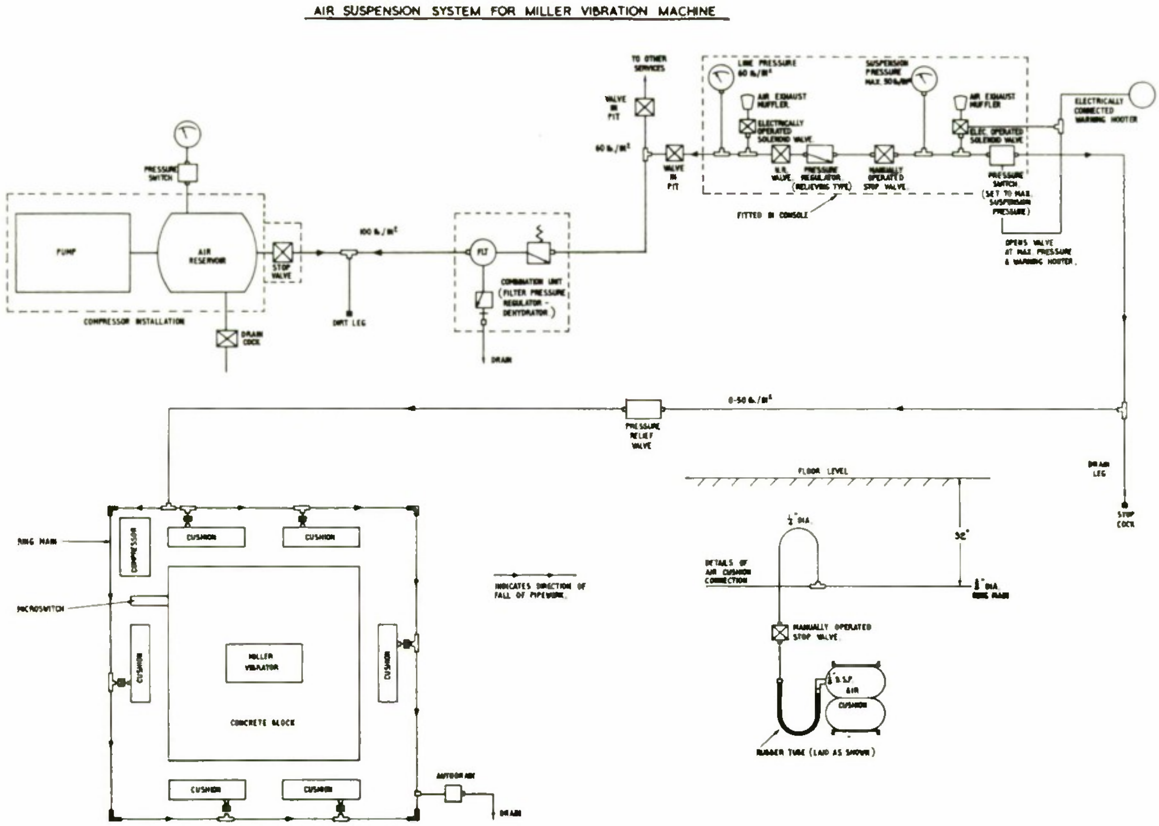

FIG. 3. Suspension system for the 2 tonne Vibration Machine.

vibration of the test table of the 2 tonne vibration machine. The speed of variation of the amplitude and frequency may be adjusted as required during a test for it was found that the original design utilising a fixed speed was not only inadequate but highly dangerous in practice. A speed variation slow enough for precision adjustment at a particular point in a test programme was found to be too slow to traverse the entire range in a reasonable period of time. It is absolutely essential that should resonant conditions occur in a test either the amplitude of vibration be reduced rapidly, or the frequency changed, to avoid damage to the machine, or as is more likely, damage to the equipment under test. A further advantage of being able to adjust the speed of variation is that the machine may be set to cover the range of amplitude and frequency in an automatic sweep to a set specification of test conditions.

Shock Test Machines

One of the minor problems encountered when considering the re-siting of the older standard lightweight shock test machines was the need to provide integral lifting facilities for each machine in order that the shock masses could be raised to give the vertical and horizontal shock blows. In the original positions use was made of the lifting arrangements provided for the building but it seemed fairly obvious that not only would this be undesirable in the new building because of the danger in continually carrying out precision lifting with the proposed five-ton crane to be installed but also because of the total number of machines which might be in operation at any given time. Each shock machine therefore required individual lifting arrangements if it was to be utilised fully. Fig. 5 gives a view of one of the standard lightweight shock test machines after modification. Complete operator and observer

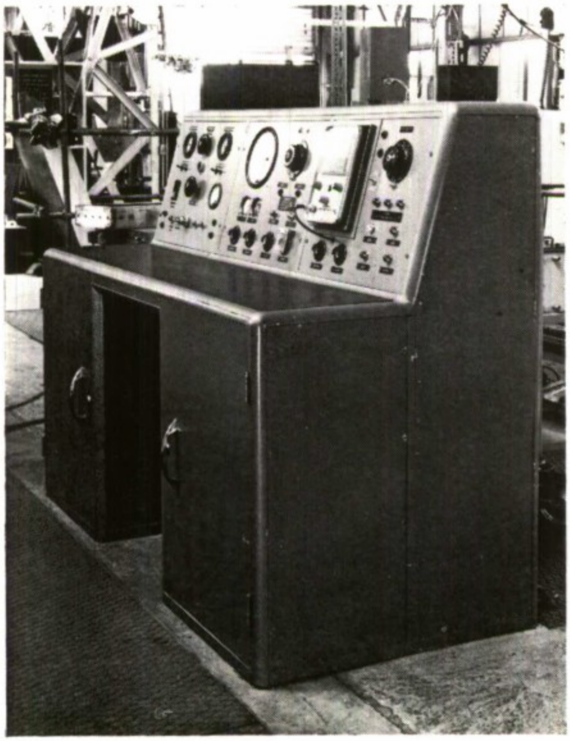

FIG. 4. Control Console for 2 tonne Vibration Machine.

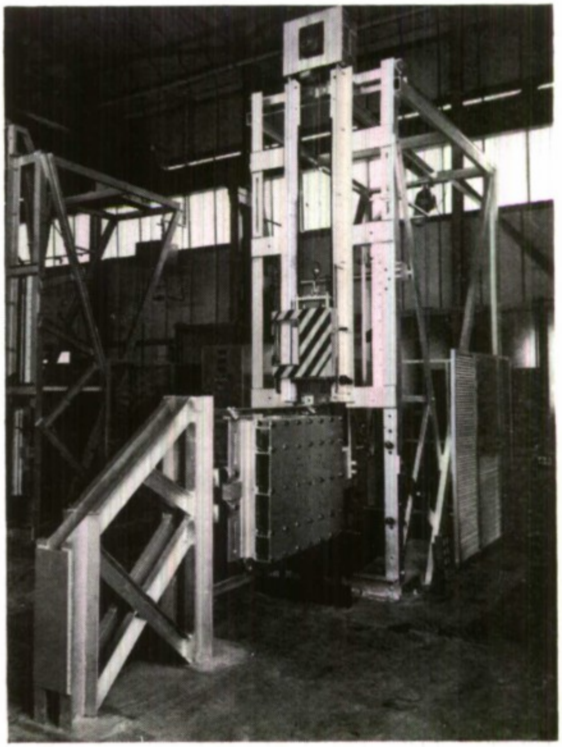

FIG. 5. Modified Standard Lightweight Shock Test Machine. Shown arranged for end blow of test item.

safety is ensured by the safety barriers and screens fitted during the modifications since the original machines incorporated none at all, being made before the Factories Acts regulations applied to the establishment. Such safety systems have to be fool and tamper-proof for it is amazing what unnecessary risks may be taken under the guise of expediency. When an observer is absorbed in a test he may also completely forget the dangers of the equipment he is using, hence the need for inherently safe procedures.

Underblow Shock Test Machine

This machine was originally designed to test submarine cells. It consists of a pendulum suspended mass of 1,000 lbs. weight which at the end of its travel imparts a vertical blow to a shock table mounted at ground level. To obtain the appropriate shock waveform a spring box is mounted beneath the table which modifies the shock pulse from the hammer. Deceleration after the shock blow is secured by mounting the table on a flexible steel plate constrained at the edges.

An unforeseen difficulty arose with the underblow machine for the original machine could not be used again as it had been in the ground for about 40 years and the effort of digging it out of its foundations would have been out of all proportion to the value of the buried framework. No drawings existed and no one could even vaguely remember its shape or size. With only the small part of the machine visible on the surface as a starting point the writer calculated what he considered to be a suitable design. When constructed it turned out to be such a huge framework that quite a few ribald remarks were made, see Fig. 6. However after it had been made an old photograph of the original machine framework came to light and basically there was very little difference between old and new.

Having resolved the modifications to the various machines it was then possible to arrive at the dimensions of the various pits and concrete foundation blocks required. As the pits for the 2 tonne vibration machine and underblow machine were so large and deep it was thought desirable to form them whilst the

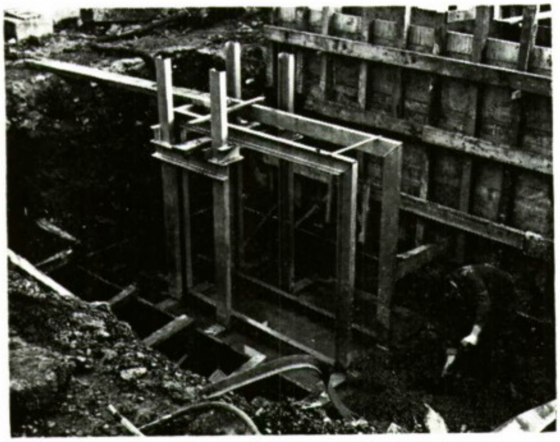

FIG. 6. Frame for Underblow Shock Test Machine.

outer foundation walls of 6 ft depth were being formed to allow the site level to be raised to that required for bringing the ballast tank for the 2 tonne shock test machine on to the site. Continuous pumping was again necessary to keep the site clear of water during this critical stage. Each pit formed was tanked with bitumen for bitter experience has taught the necessity of preventing the ingress of water. An added precaution in the case of the 2 tonne vibration machine pit was a perimeter drainage gulley to collect water in the case of a leak and thereby prevent the cork mat from becoming wet.

As soon as the concrete walls and pits had cured sufficiently the whole site was filled to a depth of 6 ft. with hardcore and consolidated to allow the delivery and installation of the 2 tonne shock test machine ballast tank. In view of the anticipated weight of the low loader carrying the large tank, it was insisted that the newly formed pit walls be braced to prevent possible damage as the cost of doing so would be very much less than the cost of reinstatement should something go wrong. Those observers present when the huge tank arrived all expressed their admiration for the way in which the low loader was reversed on to the site in spite of the very restricted approach route, and the ease with which the ballast tank, weighing 16 tons, was first lifted and then lowered into position in the pit, see Fig. 2. It all appeared so easy to the onlookers and yet a prior meeting involving about 10 people had lasted all one afternoon in order to plan and prepare for the event. One man was brave or rash enough to stand at the bottom of the pit during the lowering operation and at this stage it was fervently hoped that the calculated dimensions and subsequent civil engineering work would prove to be correct. It was a very great relief to find the tank finally sitting correctly on its foundations. Later the ballast tank was filled with pig iron obtained from Chatham Dockyard, bringing the total weight to about 120 tons although the design weight should have been 165 tons. Concrete was used to seal off the top and prevent the pig iron moving about.

The way was now clear to construct the foundations for the standard lightweight shock test machines. Many muttered imprecations were made by the workmen who had filled in the site with hardcore only a few days before and who now learned it would have to be dug out again. Site accessibility was such, however, that the lifting contractors had been compelled to specify the conditions under which they were prepared to work on the site and under these conditions the shock test machine foundations could not be constructed first. Once the various pits, foundations, cable and pipe ducts were completed it was possible to commence operations on the actual building itself. A standard steel framed building was used to keep the cost down, the only modification being the erection of brick walls 4 ft. 6 in. in height first to provide support for the numerous services necessary later. The steel framework, including the gantry crane runway, went up at enormous speed even though the erectors appeared to possess little in the way of equipment apart from spanners spiked at one end and stumpy hammers. This was to be followed by the aluminium cladding and inner heat insulation but work came to a halt when it was found that the standard building was anything but, for the dimensions of the component sheets did not tally and further sheets had to be manufactured. Even so, after more than a year's effort, the project was at last beginning to take final shape.

Electrical Supplies

Apart from the normal supplies and lighting, including optimistically, low-voltage supplies for portable electric tools; a large number of experimental supplies were necessary. Conversion machinery was going to be fitted on site originally, however the escalating building costs caused the abandonment of this

course. Extension of the existing supplies in the main electrical conversion bay then became necessary, requiring runs of aproximately 150 yards, and for these use of naval stores cables was made. One of the experimental supplies was 2,000 amperes direct current, the cable alone costing about £15 a yard (a large amount at the time). New experimental supply panels were designed to prevent all electrical danger to users, the design being a joint effort by the writer and Mr. H. W. Chambers, now at A.S.W.E. These panels too were constructed by A.E.L. staff for by now little money remained even though the cost was approaching two-and-a-half times the original estimated cost. These experimental supplies are necessary to allow the normal operation of test items undergoing shock and vibration tests.

A new cable for the three phase 50 Hz supply to the new building was deemed necessary even though it meant the construction of a new 200 yard long cable duct in the approach roadway. An existing supply was available which might just have met the anticipated requirements, experience however has shown that a 10 per cent increase per annum must be allowed for if continual and expensive arrangements for expansion are to be avoided. Within three years of commencing operations in the new building every spare circuit had been put to use due to the enormous expansion of the shock and vibration test programme and the extra equipment installed. New switchgear and distribution boards have been installed over the years to cater for the expansion, yet the original cable installed has continued to absorb the extra load without the need for replacement by a cable of higher rating.

In the left background of Fig. 1 may be seen a lean-to structure which was only about two years old at the time and was built to house the large electrical resistance and reactance units used by the Electrical Department. As it was necessary to demolish the lean-to to allow the erection of the shock and vibration facilities building a large annexe was built at the side of the new building to accommodate the displaced units. They were never installed in the annexe as the shock and vibration facilities outgrew the main building even before it was completed and the annexe had to be converted later into a supporting workshop for the adjoining facilities.

Commissioning

One of the very minor disadvantages of the site appeared shortly after the building had its window glazing installed. The writer had requested that protective wire grilles be fitted to the windows as he was familiar with the local conditions and knew what to expect. These grilles were considered by the Ministry of Public Buildings and Works to be totally unnecessary, this department having taken over the responsibility from the Navy Works Department by now. The outcome was awaited with interest although a foregone conclusion. Within 24 hours of fitting the glass practically every pane was deliberately smashed by small boys armed with catapults and stationed on the nearby road embankment overlooking the building. Even when the offenders could be seen and the police sent for to catch them the miscreants knew just what distance was necessary to the nearest inch in order to evade capture by the police officers. One could not help but admire their bravado in the face of authority. No doubt by now some of those young imps have passed through the apprentice training scheme at A.E.L. The grilles were fitted as soon as they could be delivered after that episode. Window frames were boarded up for a period to allow work in the building to continue because it was unsafe to do so otherwise with missiles whistling past staff, and in any case the building became unpleasantly cold with so much ventilation. Concern was also felt for some of the more valuable equipment as the size of the missiles increased and the building roof became littered with scores of half-bricks. The attacks soon ceased after the grilles were fitted as then the missiles produced little effect apart from the noise, even to-day however the occasional object is lobbed over hopefully.

Fig. 7 is a simplified diagram showing the sequence of events when the two tonne shock test machine is fired. As can be seen it can deliver a vertical blow only by means of the 1·25 tonne projectile which is propelled upwards at a maximum velocity of 66 ft a second (45 mph) before striking the target on the shock table. The energy after impact is absorbed by eight hydraulic decelerators (not shown in the diagram) and the ballast tank so that no energy is allowed to pass to the machine pit foundations. Four massive liquid springs support the ballast tank to ensure isolation. Details of the machine performance

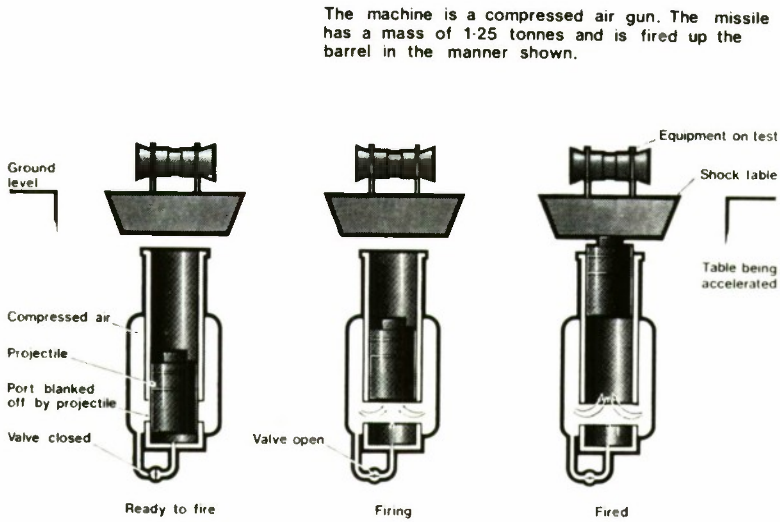

FIG. 7. Firing sequence for 2 tonne Shock Test Machine.

are given in the summary of technical data at the end of the article.

Various problems arose during the commissioning and calibration of the two tonne shock machine. The air compressor supplied by the Dockyard proved to be very much smaller in capacity than specified and the provision of the correct capacity compressor took much longer than anticipated. Emergency measures were therefore taken to obtain high pressure air supplies to enable calibration of the two tonne machine to proceed. Before long the table of the machine began to suffer under the blows of the test programme as it was a composite welded structure and the welds commenced to fail, in particular the central target area held in place by a central spider repeatedly broke loose. Many of the metal plates on the top of the table became loose through one or more welds failing and by experiment it was found that it was possible to play the National Anthem on them. Whilst interesting, no practical application for this musical effect could be envisaged. In practice however the forced vibrations in these plates under shock excitation caused spurious signals to be registered on the transducer outputs which tended to clutter the true signal. Repeated welding operations failed to keep the central part of the table in place so the writer designed a target machined from a solid block welded into the table. The local engineering firm adjacent to the establishment carried out the work in a most excellent fashion at very short notice when the work was found to be beyond the capacity of the largest machine in either of the two workshops at A.E.L. With the modification the central area of the table ceased to give further trouble.

After the calibration and commissioning was completed the two tonne shock test machine programme of work commenced. Before long it became apparent that all was not well with the machine for the piston began to stick in the cylinder. It was known that the machine at N.C.R.E. suffered from the same fault although as the fault was ascribed to a modification on the machine it was felt it could not apply to the A.E.L. machine. Investigation showed that the sealing rings on the piston had deteriorated and the bottom of the cylinder was coated with a gummy residue. Removal of the piston revealed the presence of very heavy scoring on both piston and the walls of the cylinder. Much metallic debris was found in the annular space surrounding the cylinder, including nuts and bolts and metal turnings. With reluctance it was decided to dismantle the machine and remove the cylinder for cleaning. Because of the great weight and size of the cylinder a special rig was manufactured which allowed the rotating of the cylinder whilst in a horizontal position. All the larger items of debris were removed as far as possible by hand or by the use of a vacuum cleaner, much however remained in the space surrounding the cylinder which could not be removed directly and it was decided to try to remove the remainder by

washing out with detergent solution under pressure and agitation of the cylinder. The amount of swarf etc. washed out was staggering so the process was repeated until all traces of foreign particles ceased. Two rinses with very hot distilled water followed, and a final rinse with 50 gallons of industrial alcohol to remove all traces of water and prevent the possibility of rusting. A hot air blower was used to pass a drying stream of air through the cylinder spaces to clear the alcohol, plentiful ventilation being allowed and positively no smoking allowed. A beautiful aroma hung about the building for days afterwards in spite of the plentiful ventilation. It was the biggest washing operation undertaken at A.E.L. and some idea of the size of the cylinder may be gained from the chargeman of skilled labourers working inside the cylinder to make certain that the walls would be perfectly cleaned. Opportunity was taken at the time to borrow the manufacturer's moulds used to form the rubber seals in order that new piston sealing rings could be made from a variety of synthetic materials by a local firm for evaluation later in the machine in the hope of finding a more satisfactory solution.

Several other defects were discovered in the dismantling of the two tonne shock test machine through faulty installation in the first place, including faulty assembly of the decelerator rods which necessitated machining new parts. Here mention must be made of the really excellent way in which the Electrical Department workshop dealt with the large amount of machining work suddenly thrust upon it. Modifications to the control circuits were made, new valves fitted, and so on until all the various faults were ironed out. It has to be accepted however that each time the machine is fired some deterioration is inevitable and therefore an annual refurbishing programme is necessary. New machine tables are made on a continuing basis for replacement purposes and the old damaged ones are reconditioned for further service wherever possible as the tables are expensive items. A spare piston assembly is kept in reserve together with a large kit of machine spares.

Next the two tonne vibration machine installation was partially completed in order to allow an assessment of the performance of the machine on the new isolation system. The manual controls for amplitude and frequency control were replaced by remotely operated electric motors and reduction gear boxes although left in place for use in an emergency. As far as possible the two tonne vibration machine had been stripped down and reconditioned. One of the conditions before switching on the machine is that the amplitude control be set to zero, similarly with the frequency control, and in addition the amplitude control must not be altered unless the frequency control is set above seven cycles a second. With the new remote controls these states were monitored electrically to prevent any misuse of the machine and it was therefore much to the writer's dismay when the machine was switched on for the first time after refitting to find with the controls set to minimum as indicated on the old manual control scales, that the exact opposite obtained and the aparently solid test table presented the appearance of boiling surf. After hurriedly switching off the conclusion was reached that the control position indicators had been assembled wrongly and this was in fact the case with the control for the main motor which altered the frequency of vibration. The amplitude control which adjusts the lift of the cams in the drive to the table was not susceptible so such an easy solution for the zero point seemed to wander indiscriminately and no amount of searching revealed the fault. Suspicion fell upon the reduction gearing and connecting shafts of the amplitude control system although a particularly robust engineering job. It was finally surmised that the coupling driving the shaft of the cam box was amiss in spite of the fact that no relative motion could be observed, since in theory no amplitude error could result unless slipping took place in the reduction system. The final speed of rotation of the cam box shaft was so slow and being in an inaccessible position for observation made it impossible to be certain just what was happening. Two pointers were therefore clamped in position on the parts suspected of relative motion to indicate any resulting change. With the machine in operation the amplitude control was altered up and down in the full expectation of a triumphal confirmation of logical thought. Alas—the best laid schemes of mice an' men gang aft a gley and the two pointers resolutely remained in perfect alignment. After further discussions it was elucidated from the experimental staff that the amplitude control appeared steady for some tests. A futher clue appeared when it was discovered that the coupling under suspicion had not been stripped down for examination during

the reconditioning of the machine. Eventually the writer reasoned that the slipping must only take place under certain conditions which were not encountered in the first exploratory tests. As the action of the amplitude control reduction gearing and shaft coupling is to lift the table and test item at certain positions of the drive cams, and greater resistance to change of amplitude is met with the larger test load masses, it seemed logical to assume that slipping only took place then. The largest test mass of two tonnes was placed on the test table of the machine and success was immediate.

The question might be asked why the coupling was not taken out and examined without all these tests. Such was its inaccessibility that the whole machine had to be stripped down to remove it and more than a mere suspicion was needed to justify the action. Once opened up the coupling was found to have one side with a completely sheared key, the shaft scoring proving it to have been defective for a long time. Thus the puzzle of the varying behaviour of the two tonne vibration machine in its original position before being moved to the new facilities was made perfectly clear, for the manually operated controls calibration was invariably used to set the machine to the required conditions The shearing had probably occurred through altering the amplitude control below the minimum allowable frequency. No further trouble from this cause has been experienced since there is now a protective circuit to prevent maloperation.

A lot of the doubts connected with the suspension system were removed with the first trial. It had been feared that movement in a horizontal plane might take place and some mechanical restraint such as nylon wheels acting on vertical metal guides might be necessary. These fears were completely groundless. Again it was thought that shock absorbers to restrain the vertical vibratory motion might possibly be needed, whereas the inflatable rubber pads have sufficient energy absorption on their own. No resonance of the suspension system was found to occur at any frequency, amplitude, and test mass within the working range of the two tonne vibration machine. Little vibrational transmission to the foundations takes place within the working range of the machine and the change when the block is lowered can be quite pronounced even though the cork layer is still present in the

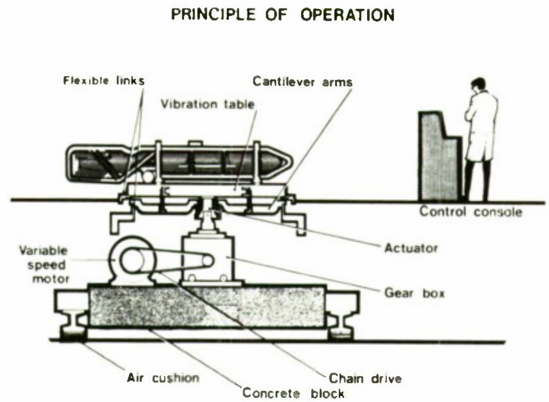

FIG. 8. Details of 2 tonne Vibration Machine and suspension system. A missile is shown mounted on the table for test.

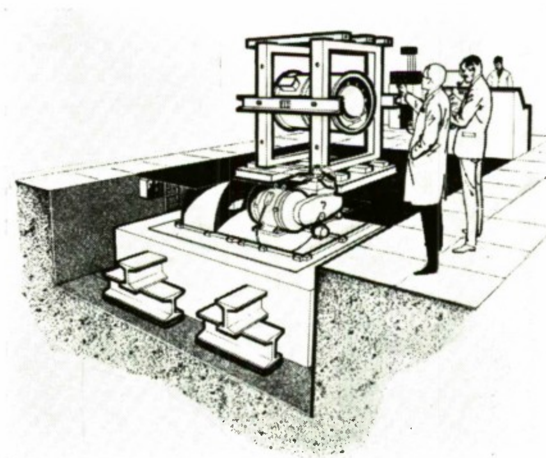

FIG. 9. Artist's impression of 2 tonne Vibration Machine in use.

lowered position, thereby demonstrating the efficiency of the isolation system. A very recent change to the machine has been the substitution of a toothed belt for the original chain drive which has resulted in a very marked reduction in the operating noise levels. Figure 8 shows a partial cross section giving details of the suspension system and the two tonne vibration machine. Figure 9 gives an artist's impression of the two tonne vibration machine in use with an axial flow fan mounted in a cube test frame fixed to the machine test table.

Improvements Continual improvements have been made since the facilities were commissioned. The toilets and washing facilities deleted from the first phase have been built for some time now. Offices for the staff have been built adjacent to the test areas although sufficiently removed to attenuate the worst of the noise generated, for the nature of the work decrees a very noisy environment, which it is difficult to ameleriorate. Similarly the industrial staff have a workshop adjacent to the test area to avoid unnecessary exposure to the noise. A scheme is in hand to fit a sound reduction system in the main building to cut out the reflected sound energy in a similar manner to the Festival Hall treatment. Each member of the staff employed in the Shock and Vibration facilities is personally responsible for protecting his ears against damage, individual sets of ear defenders are supplied for this purpose. They are not pleasant devices to wear continuously because of the unpleasant perspiration which gathers under the plastic ear muffs and for the sake of hygiene they must be kept scrupulously clean, in addition they may lead to dangerous situations as shouted warnings may not be heard. In a building where continuous lifting and moving of heavy test items takes place one needs to exercise every caution if accidents are to be prevented. All the machines for shock tests are fitted with individual distinctive alarm systems to warn personnel of the need to guard their hearing without forcing them to wear ear defenders all the time and thereby endangering their persons in other ways.

Other improvements include the motorisation of the lifting facilities which rising costs had prevented from being fitted in the first place, a motorised roller shutter door, and more recently an annexe of about one quarter of the main shop area for the housing of a new shock machine operated from the stored energy in steel springs. Whilst the new deck shock machine cannot give accelerations of the same order of magnitude as the two tonne shock machine it has the great advantage of being able to deliver blows in the vertical or horizontal planes. Previously shock tests on the main two tonne shock test machine in other than the vertical plane of the test item have necessitated mounting the test item in the position so that the vertical blow delivered by the machine would pass through the plane required and the resulting test is not a true representation of what would be met with in practice.

Instrumentation

Accurate recordings of the monitored data is most important when quite often tests cannot be repeated. Outputs from the various devices such as accelerometers, velocity meters, etc., are recorded on storage oscilloscopes and photographed where necessary to provide a permanent record. High speed photography at up to 10,000 frames a second also aids analysis of events far too rapid for the unassisted eye to appreciate. These photographs are of course taken by the expert staff of the photographic section. Slowed down to normal rates of projection the films enable a degree of understanding of high speed phenomena to be gained which would otherwise be completely impossible. Stroboscopes are very useful for the examination of items subjected to vibration tests for what seems a comfortable blur to the unaided eye is often quickly revealed to be a potential trouble spot. Other essential instrumentation includes devices for the accurate measurement of amplitude and frequency in vibration tests.

Safety

Some mention has already been made about safety. In the case of the 2 tonne shock machine it is deemed dangerous to be in the adjacent test area when the machine is operated. The 2 tonne shock test machine operator therefore controls the machine from some distance away behind armoured glass in a raised control and observation room. He has complete control of the final operation when firing the machine. Other observers must stand behind the safety barrier shown in Fig. 10. Anyone entering the area during a test operates safety circuits which then prevent the machine from firing. Due to the strict precautions only one serious mishap has occurred and fortunately no one was in contact with the table when the machine was fired acidentally, the only damage being caused by the loose items being hurled through the laboratory. The person responsible was removed from these duties immediately for safety regulations are designed to avoid unnecessary risks and often seem petty restrictions until a nasty accident occurs.

The vibration machines present little potential danger. Vibration induced noise can be very irritating as the test periods take some

FIG. 10. General view of Shock and Vibration Test Laboratory.

time to complete, even if the noise levels reached do not approach danger zones. Possibly more danger exists from personnel standing on the table during a test as the human frame is not made to withstand such treatment[9]. As it appears to be a natural reaction to move off there seems to be little point in displaying notices to keep off the table during vibration tests.

There is no possible doubt that working in the Shock and Vibration laboratory results in the staff concerned being subjected to stress not encountered in normal working conditions. Changes in staffing are made at intervals to reduce the effect of such stress to a minimum.

General Description of Facilities

Fig. 10 gives a general view of the Shock and Vibration laboratory. To the far left may be seen the raised control room for the 2 tonne shock test machine, entered by the short flight of stairs, through the toughened observation windows may be seen the control panel for the machine and some of the recording equipment. The 2 tonne shock test machine table is slightly right of centre in the background with the safety barrier fixed across the building marking the shock test area. In the centre ground may be seen the slightly raised table of the 2 tonne vibration machine above its checker plate surround and with its control console to the right. The two large panels on the extreme right are two of the four experimental supply panels with the 415 volt 3 phase 50 Hz supplies distribution panels and associated switchgear located midway between. On the opposite side facing the 2 tonne vibration machine are the two original small vibration machines, one for horizontal, the other for vertical vibration, with the electronic speed control circuits for the drive motors in the nearby console. To the immediate right are the components of the piston assembly which forms the projectile of the 2 tonne shock test machine. In the immediate foreground is the furthest one of the two modified standard lightweight shock test machines, the nearest one not being visible in the photograph, the raised lever suspended by the cable is used for automatically raising and releasing the 400 lb. hammer for the horizontal blows. Immediately in front of this shock machine is the underblow machine which uses a 1,000 lb. hammer and which has a submarine cell mounted in position for a shock test.

Electric heaters maintain the temperature above 50°F, even when the steam heating is shut off, additional heating is placed in the pits of the 2 tonne shock machine and 2 tonne vibration machine to prevent condensation troubles in the event of cold weather.

Summary of Technical Data

2 Tonne Shock Test Machine

Weight of table: 1620 kg (1·6 ton).
Weight of projectile: 1279 kg (1·25 ton).
Maximum acceleration for 1900 kg (1·875 ton) on table: 280 g.
Maximum velocity for 1900 kg (1·875 ton) on table: 6 metres/sec (20 ft/sec).
Maximum impact force on table: 900 tonne.
Maximum retardation force on table (decelerators): 500 tonne.
Maximum projectile velocity: 19·8 metres/sec (66 ft/sec).
Maximum displacement of table: 57 mm (2·25 in)
Table area: 2·4 × 1·2 metres (7·5 × 4 ft).
Working stroke: 2·55 metres (8 ft 6 in).
Internal dia of Cylinder 500 mm (19·5 in).

Standard Lightweight Shock Test Machine

Two of these are in use, one being modified to use an American Type Shock Plate for tests carried out to Mil. Spec.
Weight of hammer: 180 kg (400 lb).
Weight of shock plate: 320 kg (700 lb).
Maximum velocity no load: 2·9 metres/sec (9·5 ft/sec).
Maximum acceleration no load: 200 g.
Maximum velocity 204 kg (450 lb) load: 2 metres/sec (6·5 ft/sec).
Maximum acceleration 204 kg (450 lb) load: 90 g.

Underblow Shock Test Machine

Weight of table: 320 kg (700 lb).
Weight of hammer: 450 kg (1000 lb).
Maximum velocity no load: 3·65 metres/sec (12 ft/sec).
Maximum acceleration no load: 250 g.
Maximum velocity 680 kg (1500 lb) load: 2·45 metres/sec (8 ft/sec).
Maximum acceleration 680 kg (1500 lb) load: 40 g.

Deck Shock Test Machine

Now being installed and designed to give simulated horizontal or vertical shock blows. Typical figures for a load of 545 kg (1200 lb) are:
Velocity: 5·5 metres/second (18 ft/sec).
Acceleration: 90 g.
Displacement: 63·6 mm (2·5 in).
Frequency: 26 Hz (approximately).

2 Tonne Vibration Machine

Also known as the Miller Vibration Machine.
Maximum load: 2 tonnes.
Maximum amplitude at 14 Hz:
± 1·27 mm (± 50 thou. in).
Maximum amplitude at 23 Hz:
± 0·456 mm (± 18 thou. in).
Maximum amplitude at 33 Hz:
± 0·0127 mm (± 5 thou. in).

Small Horizontal Vibrator

This machine is designed to give horizontal vibration. The vibration plate is driven by a variable speed motor through eccentric shafts, the amplitude heing variable in finite steps by changing these shafts.

Maximum load 270 kg (600 lb).
Maximum amplitude at 14 Hz:
± 1·27 mm (± 50 thou. in).
Maximum amplitude at 23 Hz:
± 0·456 mm (± 18 thou. in).
Maximum amplitude at 33 Hz:
± 0·0127 mm (± 5 thou. in).

Small Vertical Vibrator

This is a small machine with an adjustable shaft which gives three fixed amplitudes in a vertical mode in a similar way to the horizontal vibrator.

Maximum load—22·5 kg (50 lb).
Amplitudes and frequencies are similar to those quoted for the horizontal machine above.

Electro-Hydraulic Vibrator

This machine consists of an hydraulic actuator driven by an oil pump operated by an electric motor. Facilities are provided for variation of frequency and amplitude and for displaying the displacement wave form.

Electro-Hydraulic Vibrator

Thrust	*Freq.*	*Amplitude*
100 kg (2200 lb)	2 Hz	± 19·0 mm (750 thou. in)
100 kg (2200 lb)	10 Hz	± 2·54 mm (100 thou. in)
100 kg (2200 lb)	30 Hz	± 0·254 mm (10 thou. in)
100 kg (2200 lh)	100 Hz	± 0·004 mm (0·2 thou. in)

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Acknowledgement

Figures 7, 8 and 9 were supplied by the Technical Illustrator's Pool (Naval) for use during the Golden Jubilee Open Days held July 1970 at A.E.L., West Drayton, Middlesex.

S.E.R.L. AT THE 1972 PHYSICS EXHIBITION

Navy Departments interests at the 1972 Physics Exhibition at Alexandra Palace were represented solely on this occasion by S.E.R.L.

The displays presented covered Pulsed atmospheric pressure CO_2 laser parameters and Thermal imaging with a pyroelectric Vidicon. Descriptions of these exhibits, both of which attracted considerable interest, are given below.

Pulsed Atmospheric Pressure CO_2 Laser Parameters

Reliable operation of pulsed atmospheric pressure transversely excited CO_2 lasers depends upon the uniformity of the gas discharge within the resonator. In the laser exhibited, a very uniform discharge occurs between two identical solid electrodes with Rogowski profiles. A fine wire placed parallel to the electrodes but offset from the centre line, is connected to the cathode by small coupling capacitors. When a high voltage pulse is applied to the main electrodes, using a rapid discharge capacitor, a triggered spark gap and low inductance connections, field emission from the wire initiates a very diffuse discharge in the gas at atmospheric pressure between the main electrodes along their whole length. If the wire is not present a single bright arc occurs. The laser produces an output energy density of 18 J l^{-1} at a wavelength of 10·6 μm. The results of a parametric study of the discharge shows the influence of the CO_2-N_2-He gas composition on factors such as the arcing limits, pulse energy, peak power, pulse width and time delay. Properties of the discharge and the laser were demonstrated.

Thermal Imaging with a Pyroelectric Vidicon

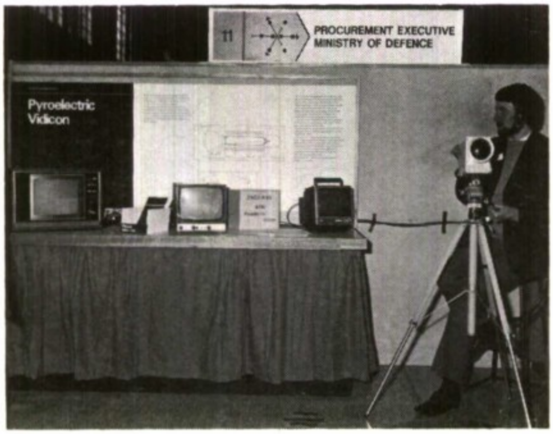
Thermal imaging with a pyroelectric Vidicon can provide a real time television presentation of Thermal scene with a temperature resolution of about 1°, a spatial resolution of 2 mrad and frame rates of about 10 s^{-1}. The equipment is uncooled and should provide a relatively low cost alternative to scanned photon detector systems.

An infrared transmitting lens of a suitable mirror system focuses a thermal scene through a chopper on to a thin pyroelectric crystal which replaces the photoconductive target in a normal vidicon tube. In addition, the Vidicon tube has an infra-red transmitting faceplate. The crystal is in the form of a disc with the pyroelectric axis normal to its plane. Such a pyroelectric crystal produces an electrical signal proportional to its temperature change, thus if static scenes are to be detected such changes must be introduced artificially, for instance by use of a rotating chopper. The thermal image on the pyroelectric produces a charge pattern with the same spatial and intensity variation as the thermal scence.

The front surface of the crystal is covered with a semi-transparent conducting film and is

thus an equipotential surface. The pyroelectric voltage distribution therefore appears on the rear surface of the target. This is scanned with an electron beam and the signal current drawn used to z modulate a television display scanned in synchronism with the electron beam. Practical limiting noise sources are either amplifier noise or shot noise in the Vidicon tube.

Much of the early experimentation with the pyroelectric Vidicon has been carried out using a demountable apparatus at S.E.R.L., but in parallel with this, work has proceeded under a CVD contract at the English Electric Valve Company Limited, Chelmsford, where sealed-off tubes have been produced.



THIRD SHIP CONTROL SYSTEMS SYMPOSIUM

This Symposium will be held at the University of Bath from 26 - 28 September 1972. Over 70 papers by representatives from all over the world will be read. Further details of the technical programme are available on request from:

J. B. SPENCER,

Ship Department, Section 601, Block B,
Ministry of Defence,
Foxhill, Bath, U.K.

Centenary of the Admiralty Experiment Works

This centenary was marked with an Open Week beginning on April 10. During this week some 4,000 people visited the Establishment including senior management from shipyards, ship owners, associated industries, heads of research establishments, senior university staff, as well as the families of our own staff. In addition on Friday, April 14, nearly a hundred members of the R.I.N.A. visited A.E.W. and after a formal presentation of a technical paper in the morning, they toured the exhibitions after lunch.

The first ship model test tank originated from a proposal by William Froude, a Civil Engineer of considerable ingenuity and skill who had for many years been interested in ship model testing. He had undertaken some rather crude model tests in the River Dart and had devised a method of predicting full-scale ship performance from model data. His proposal to the Board of Admiralty in 1868 pointed out that there were serious discrepancies in the then current ideas about ship resistance, and claimed that his work had demonstrated that accurate estimates of ship resistance could be made from model tests. He proposed that a Towing Tank should be built, equipped and run for two years for a sum of £2,000 to undertake basic studies of frictional resistance followed by a limited number of tests of ship models in service, and ultimately to proceed to a methodical investigation to the effect of form on resistance.

The Board accepted this proposal in 1870 provided that the work was extended to include the subject of ship rolling. Progress was rapid, building commenced at Torquay in June 1870 and the first experiment was run on March 3, 1872. This involved a model of H.M.S. *Greyhound,* a ship which had previously been towed to measure her full-scale resistance.

The tank at Torquay was in use until 1886 when the lease expired. During this period William and his son R. Edmund Froude, who took over on the death of his father in 1879, laid the foundations for almost all experimental techniques used on models of surface ships. Frictional resistance coefficients were obtained which are still in use to-day, rules governing the choice of form established and the testing of propellers initiated. Other work was carried out on the interaction between hull and propeller, on statical stability, rolling and wave profiles.

The move to the present site at Haslar in 1886 coincided with a big increase in the naval shipbuilding programme. By 1918 some 500 different warship designs had been tested, representing

> 33 Battleships, 46 Cruisers, 61 Destroyers, 14 Submarines and 20 miscellaneous ships.

The vast Fleet of the first World War had all been tested in model form in the Haslar Tank.

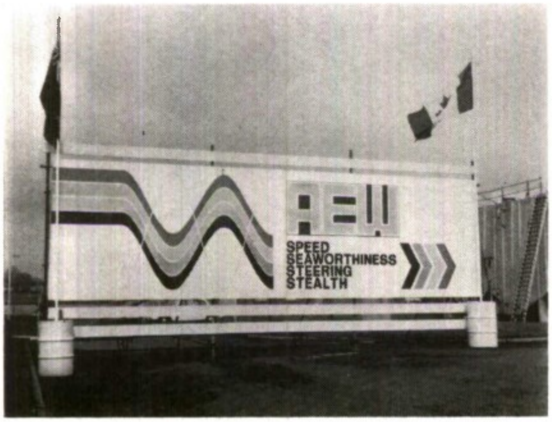
Between the wars most of the very limited resources available were devoted to re-equipping the Works and to building a second, larger towing tank. Considerable effort was applied to the study of manoeuvrability, particularly of destroyers, using Horsea Lake.

The first cavitation tunnel was installed early in World War II and led to considerable improvement in the speed of fast craft.

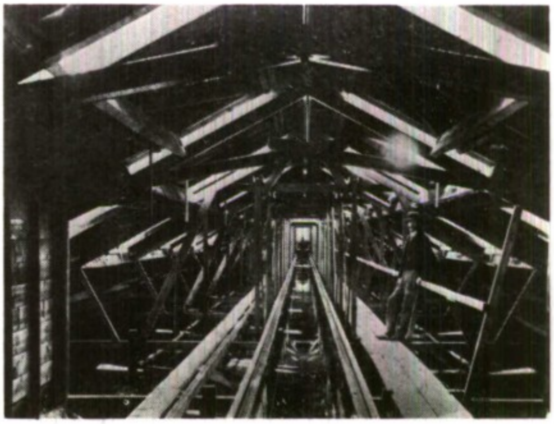
Two photographs of the displays appear . . . and a further article will appear in a later issue. One of the highlights of the show was a film entitled "Shaping To-morrow's Warships" which shows how A.E.W. influences the underwater hull form and propellers of all British warships to obtain optimum performance under the headings

Speed, Seakeeping, Steering and Stealth.

This film, which lasts 28 minutes, may be borrowed on application to the Superintendent.



The Entrance Placard.


Froude's Torquay Tank

NOTES AND NEWS

Admiralty Surface Weapons Establishments

Mr. H. C. Hocking retired in February 1972 after 46 years service to the Crown. He joined the Navy as an artificer apprentice in 1926, and between then and his retirement as a Lt. Cdr. (L) in 1961, he saw service in almost every theatre of operations and gained wide experience of warships and their operational role. Having changed his more formal service uniform for the less formal one of an Experimental Officer, he was well-suited to be in charge of the Ship Installation Engineering Section at A.S.W.E. which has the responsibility for the installation development and planning arrangements for all the communications, radar and associated equipment for a large proportion of the Running Fleet as well as some new-construction ships.

In his youth, Mr. Hocking was a first-class boxer and rugby player. In more recent years his interests have turned to sailing, gardening and wine-making. His many friends and colleagues wish him and his wife Joan a long and happy retirement.

Mr. P. R. Clynick, the Head of A.S.W.E's. Computer Research Division, has taken up his new appointment as Head of the Mathematical Group at A.R.L.

Dr. G. Harries visited the Defence Communications Agency in Washington during February to discuss the technical parameters of the next generation of satellites to be used jointly by the U.K. and the U.S. The Navy has a strong interest in satellites being developed for defence use by other nations to enable the present R.N. shipborne satellite terminals to be compatible with other space segments and so ensure world coverage of communications by satellite.

Mr. K. R. Morgan visited the headquarters of the International Association of Lighthouse Authorities in Paris to attend a meeting of the sub-committee on Microwave Aids to Navigation. Part of the work of the sub-committee is to prepare proposals for a specification for radar transponder beacons and TX Division of A.S.W.E. was asked by the Executive Committee to provide the U.K. technical specialist.

Dr. D. Kiely, Dr. W. Whitlock, M. H. A. Smith and P. F. C. Griffiths attended a major U.S.N. exercise LANTREADEX 3 - 72 during February 1972. A force consisting of aircraft carriers, D.L.Gs., frigates and submarines from the U.S.A., U.K. and the Netherlands took part in various phases of an exercise which was designed firstly to provide training for weapon system personnel in a multi-threat environment, and secondly to measure the degradation in overall weapon system effectiveness in such an environment. The members of the R.N.S.S., supported by naval officers from A.S.W.E., supervised the collection of data during missile firings from H.M.S. *London* and H.M.S. *Glamorgan*.

Mr. Peter Kirk; M.P., Under-Secretary of State for the R.N., accompanied by his Assistant Private Secretary Mr. L. A. Richardson, recently arrived at Fort Southwick by helicopter to visit A.S.W.E. The object of his visit was to familiarise himself with the work of the establishment. The Director, Mr. H. W. Pout, briefed him on A.S.W.E.' activities and organisation, and he was later taken on a tour of the establishment. He was shown some aspects of radar research and demonstrations of new radar techniques of particular importance to naval radars. He also saw H.M.S. *Bristol's* weapon systems equipment, the workshops and the establishments' microlfim unit.

Admiralty Compass Observatory

John Lawrence Howard, ACO's first and last Chief Experimental Officer, has retired after 34 years service.

After his education at Plumstead Technical School and Woolwich Polytechnic, he joined the electrical engineering firm of Messrs. Johnson and Phillips at Charlton, initially as a student apprentice and later becoming a Junior Engineer. His primary duties were in the development of high voltage switch-gear and high tension cable.

In 1937, when war seemed imminent, he joined Admiralty Service as a Technical Assistant III, being appointed to ACO and seconded to work with the late Alfred Hine in the group engaged on the development of magnetic compasses. Perhaps the outstanding project of his first few years was the successful evolution of a magnetic compass from which heading transmissions could be derived—the ATMC. The bowl of this compass was filled with an electrolytically conducting liquid and the card carried electrodes which formed part of a wheatstone bridge circuit. Card deflection gave rise to a bridge unbalance potential, balance being restored by a motorised servo system, which provided power drive to M-type transmissions.

In 1944 Jack Howard moved to Canada as ACO's representative with an Admiralty Technical Mission dealing with magnetic compass affairs. In the same year he was promoted to Technical Officer.

Returning from Canada in 1945, Howard continued work with the Magnetic Compass Group, now moving into the development of gyro-magnetic compasses. This class of instrument incorporated the north-seeking and transmitting capability of the ATMC with an azimuth damping contribution from a small gyro. In addition, the AGMC's embodied sophisticated methods of applying corrections for variation and deviation. As well as work for the Navy, the Group designed and developed a miscellany of magnetic compasses for Army, Air Force and civilian use.

Having been metamorphosed into an Experimental Officer in the post-war reconstruction of the Scientific Civil Service, Howard was promoted to Senior Experimental Officer in 1953. On the retirement of Alfred Hine he succeeded to the post of Head of the Observatory's Magnetic Group.

Among the many and diverse projects undertaken by the Group were the design of a projector compass for Sir Vivian Fuch's Antarctic 'Snowcats'', underground directional equipment for the National Coal Board, magnetic sensors for sonobuoys, Magnetic Anomaly Detection for Nimrod aircraft and magnetic surveys of airfields at home and abroad.

By virtue of his long experience in magnetic matters, Howard latterly became a consultant and adviser in this field to a number of organisations, including RAE, BOAC and BEA. Also, he and his colleagues operated an intramural service of " safe distance " measurements on industrial equipment for the Services as well as carrying out precise measurements of direction and magnitude of the earth's magnetic field and of the magnetic properties of numbers of materials. As leader of the British delegation to the International Standards Committee on Magnetic Compasses he performed a difficult task with considerable distinction, their work culminating in the production of a very workable family of standards.

Jack Howard's declared hobbies are bowls, bees and money, the last-named being an end product of a successful Stock Exchange investment club run by him. His magnetic personality doubtless will continue to attract substantial dividends !

At a farewell gathering at the Observatory, Mr. H. J. Elwertowski, Head of ACO, paid tribute to Jack's long and outstanding services and presented him with a crystal glass decanter set on behalf of his many friends and colleagues. Mr. and Mrs. Howard intend to retire to Wimborne in the County of Dorset and they carry with them the warm good wishes of all their friends at ACO.

BOOK REVIEWS

Photomicrography. R. P. Loveland. Wiley & Sons Inc., 1970. 1037 pp. Price £18·50.

Consisting of over a thousand pages in two volumes, this book is a worthwhile, although very expensive, addition to the already prolific material covering the field of microscopy and photomicrography. Not only is this a useful textbook and reference book but there is also a considerable amount of practical material and many commercial microscope systems are covered in some detail. A niggling criticism is that Mr. Loveland's affiliation to the Eastman Kodak Company seems to have precluded discussion of photographic materials supplied by other sources such as Ilford, Agfa and British Kodak.

After beginning with a general survey of microscopy the first volume goes on to deal with reflected and low power photomicrography using the compound microscope, illumination, image contrast and ends with a chapter on cameras.

The second volume covers the various methods of object illumination, flash, infrared, ultraviolet, fluorescence and cinematic photomicrography. Several chapters are also included giving detailed discussion of the correct exposure and processing of photographic materials.

The book is fully up-to-date as is indicated by a large section on holographic methods of microscopy. John Wiley's high standards of production are maintained; there are many clear tables and diagrams and some superb colour photographs. The device of printing important passages in bold type merits emulation by other authors.

This book can be thoroughly recommended both to the expert and to the neophyte.

M. J. Beesley

Applied Heat for Engineers. By J-B. O. Sneeden and S. V. Kerr; Pp. xv+420 (Paperback). Blackie. Price £1·90.

This book on engineering thermodynamics is intended both for those studying for the examination in Applied Heat of the many professional institutions, and for students embarking on a degree course. Its intended purchasers have been borne in mind in its production in paperback form, at a comparatively low price.

The first three chapters present an introduction to the subject, covering units and defini tions, pressure and its measurement, and thermometry. The second part of the book covers heat and work, the first and second laws of thermodynamics, the thermodynamic properties of liquids, vapours and gases, changes of phase and state diagrams, and processes executed by perfect gases in a closed system. The third and final section discusses the applications in engineering of the properties treated in the second part, namely engine cycles, applications of the first law, steam power cycles, steam power plant, blowers and compressors, gas-turbine power plants, refrigeration, air conditioning, heat transfer, and fuels and combustion.

This fourth edition has been completely revised, and, in accordance with the modern approach, the SI units are used throughout. Questions (with solutions) are given after each chapter, and an index to the tables used throughout the text is also icluded. The volume is well endowed with diagrams, together with some very ambitious and well done drawings. Thermodynamics is notorious for its mathematics content, and this book is somewhat formidable in this respect, especially bearing in mind that a good engineer is not always a good mathematician. However, there is a great deal of information presented in it, and it should have substantial appeal to students concerned with this subject.

J. R. Kirby

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All communications should be addressed to:—

The Editor,
Journal of the Royal Naval Scientific Service.
Ministry of Defence,
Station Square House,
St. Mary Cray, Orpington, Kent. BR5 3RF
Telephone: Orpington 32111, ext. 345.
Telex: 896394

Information Centre
Knowledge Services
[dstl] Porton Down,
Salisbury
Wilts
SP4 0JQ
Tel: 01980-613753
Fax 01980-613970

Defense Technical Information Center (DTIC)
8725 John J. Kingman Road, Suit 0944
Fort Belvoir, VA 22060-6218
U.S.A.

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